Applied Energy 191 (2017) 639–652

Contents lists available at ScienceDirect

Applied Energy

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

Combined heat and power from the intermediate pyrolysis of biomass materials: performance, economics and environmental impact

Y. Yang [a,*], J.G. Brammer [b], D.G. Wright [a], J.A. Scott [a], C. Serrano [a], A.V. Bridgwater [a]

[a] European Bioenergy Research Institute (EBRI), Aston University, Birmingham B4 7ET, UK
[b] Department of Chemical Engineering, University of Chester, Thornton Science Park, Chester CH2 4NU, UK

HIGHLIGHTS

- Performance of the Pyrolysis and CHP systems is studied and evaluated.
- Overall CHP efficiency of the 1000 kg/h Pyro-CHP system is 42.5%.
- Levelised Energy Cost is high, but the optimistic scenario is potentially profitable.
- Life-cycle GHG analysis shows strong positive environmental benefits.

ARTICLE INFO

Article history:
Received 2 November 2016
Received in revised form 31 January 2017
Accepted 1 February 2017

Keywords:
Bioenergy System
Intermediate Pyrolysis
Combined Heat and Power
Techno-economic Evaluation
Environmental Life-cycle Analysis

ABSTRACT

Combined heat and power from the intermediate pyrolysis of biomass materials offers flexible, on-demand renewable energy with some significant advantages over other renewable routes. To maximise the deployment of this technology an understanding of the dynamics and sensitivities of such a system is required. In the present work the system performance, economics and life-cycle environmental impact is analysed with the aid of the process simulation software Aspen Plus. Under the base conditions for the UK, such schemes are not currently economically competitive with energy and char products produced from conventional means. However, under certain scenarios as modelled using a sensitivity analysis this technology can compete and can therefore potentially contribute to the energy and resource sustainability of the economy, particularly in on-site applications with low-value waste feedstocks. The major areas for potential performance improvement are in reactor cost reductions, the reliable use of waste feedstocks and a high value end use for the char by-product from pyrolysis.

1. Introduction

1.1. Background

Over ten percent of total world primary energy supply in 2013 (13.5 billion tonnes of oil equivalent) was produced from biomass sources, making biomass by far the most important renewable energy source [1,2]. In a global context, the use of biomass to generate power and heat has been a key element in reducing fossil fuel consumption and combating climate change. In the UK, the government has projected bioenergy to contribute over 35% of the total renewable energy production (including non-domestic heat and transport) needed to meet the target of 15% primary energy generation from renewables by 2020 [3].

Biomass as an energy source is abundant, predictable and non-intermittent, and, importantly, is largely "carbon neutral" if sustainably managed. Furthermore, it is the only alternative source of fixed carbon for the manufacture of carbon based fuels and chemicals. Over the past 35 years, converting solid biomass material to liquid and gaseous biofuels through thermal conversion processes (pyrolysis and gasification) has been attracting attention both for scientific research and for industrial commercialisation, as they are considered as promising technologies for cleaner energy production [4–8]. Pyrolysis is a thermal process in which an organic feedstock decomposes at elevated temperatures (usually between 450 and 550 °C) in the absence of oxygen. Three product phases are simultaneously produced, namely pyrolysis liquid (consists of pyrolysis bio-oil and pyrolysis water), combustible gases and char with potential for fuel applications. The pyrolysis liquid is particularly interesting, as it is an efficient energy carrier due to high energy density and has the advantage of application in engines [9]. Combined Heat and Power (CHP) is an effective and

* Corresponding author.
E-mail address: y.yang6@aston.ac.uk (Y. Yang).

http://dx.doi.org/10.1016/j.apenergy.2017.02.004
0306-2619/

efficient method of energy production as it simultaneously generates electrical power and heat (in the form of steam or hot water) in a single process. Diesel engine based stationary generating systems generally have high fuel quality tolerance and can use liquid biofuel. In a typical diesel engine CHP arrangement, approximately 45% of the total energy input is recoverable as heat from the engine cooling and exhaust gas system in the form of hot water and approximately 40% is converted to electricity. This "co-generation" method therefore uses much less fuel compared to the separate generation of power and heat [10].

Research and technology development of integrated biomass pyrolysis and CHP process has attracted attentions in the recent a few years. Kohl et al. [11] investigated the integration of biomass fast pyrolysis within a CHP plant. The results showed that the process integration strongly improved the CHP's energetic and environmental performances. The operation hour of the plant can be increased by up to 57% by providing lower district heating loads. When concerning the optimisation of district heating energy efficiency, the authors concluded the pyrolysis products (oil and char) should be sold to market rather than internal use. Van de Beld et al. [12] carried out a series of experimental investigations into the use of pyrolysis oils and pyrolysis oil derived fuels in diesel engines for CHP applications. A duration experiment of 40 h with pyrolysis oils was carried out without notable negative effect on exhaust gas emissions and fuel consumption [13]. Despite satisfactory results achieved, the authors also pointed out that some specific properties of the oils (e.g. low heating value, low ignition ability, high water content and high sensitivity to repolymerisation) caused difficulties in direct diesel engine applications. These aspects needed to be taken into consideration when upgrading the oils for improvement. Industrial development of the integrated biomass pyrolysis and CHP plant was firstly demonstrated by Fortum Oyj. in 2013 at Joensuu Finland [14]. A fast pyrolysis system (50,000 L/year fast pyrolysis oil) has been integrated to a CHP system with a production capacity of 50 MW for electrical power and 140 MW for heat (mainly district heating supply). The pyrolysis oils produced are consumed on-site to replace heavy fuel oil, which equals to about 10 MW in energy production [14].

As with any novel energy system, it is necessary to understand the overall performance and environmental and economic impacts of schemes at various scales to ensure that effort and investment are targeted at the areas of greatest potential impact. Techno-economic and environmental assessments of pyrolysis to energy systems are being increasingly undertaken with recent contributions in the area of small scale power generation by Shemfe et al. [15], and CHP from fast pyrolysis by Rogers et al. [16] and Bridgwater et al. [17]. Exergoeconomic assessment of CHP-integrated biomass upgrading were carried out by Kohl et al. [18] to evaluated the energy efficiency and energy production cost on using different feedstocks and integration options. Consideration of non-energy applications of pyrolysis is an increasingly important aspect of this work as discussed by Kuppens et al. [19] who examine phytoremediation as an alternative motivation for developing pyrolysis projects.

1.2. The intermediate pyrolysis process

Development of a pilot-scale intermediate pyrolysis technology commenced at Aston University in 2008. A larger scale technology demonstration started in 2012 (maximum 100 kg/h throughput – Fig. 1). The core of the intermediate pyrolysis system is a co-axial dual (inner screw and outer) screw pyrolysis reactor, which operates in a temperature range of 450–550 °C and with a much longer solids residence time (2–10 min) compared to conventional fast pyrolysis (detailed design features can be found in [20,21]). Depending on the type of feedstock and processing conditions, the product yields are 10–30% liquid (pyrolysis oil and water), 15–20% gas and 50–75% char. During reactor operation, the inner screw conveys a mixture of fresh feedstock and recycled char product forward through the reactor, and the outer screw returns a portion of the char product backwards for recycle to achieve internal char recycling. Hot recycled char can act both as the heat carrier and as the catalytic cracking medium (due to the presence of ash in the char [22]) thereby enhancing the secondary cracking reactions for pyrolysis vapours. This results in the production of a greater fraction of permanent gases and lower molecular weight condensable organic components and less heavy tars.

Despite the relatively low liquid yield compared to conventional fast pyrolysis which is designed to maximise this yield, the intermediate pyrolysis process may deliver superior overall performance when the quality of all the products of pyrolysis are considered. The products are in three forms:

(1) A two phase liquid where the organic phase (pyrolysis oil) can be easily separated from an aqueous phase under gravity. The pyrolysis oils, in blends with up to 50% biodiesel, can be used in unmodified diesel engines for heat and power [21,23,24].
(2) A valuable char product which can be used as charcoal for combustion or bio-char as a soil enhancer. If processing high-moisture content feedstocks, the char can acquire the characteristics of activated carbon due to comprehensive interaction with steam [25].
(3) A high-quality fuel gas that contains over 50% combustible gases (H_2, CH_4 and CO) with the reminder mainly being CO_2 [21]. The screw-based reactor usually does not require large quantities of inert gas (usually nitrogen) as a transport or fluidising medium (as is the case with the conventional fluidised bed pyrolysis reactors), which normally remains as a part of pyrolysis gas and causes dilution of pyrolysis gas with reduced heating value.

Furthermore, the intermediate pyrolysis reactor can process difficult low-value high-ash waste feedstocks (such as sewage sludge and de-inking sludge) that cannot be processed by fast pyrolysis, as reported by previous work on pilot-scale investigation [23,24]. This is due to the fact that the reactor is based on screw conveyers rather than gas/liquid fluidisation.

1.3. Aim of the work

The intermediate pyrolysis technology was originally developed at Aston University, and there has been a series of laboratory based experiment carried out from bench to pilot scale investigating the production of pyrolysis oils and other products for fuel application purpose. Following the previous work, this work evaluates the integrated fuel production and energy production systems with consideration of technical, economic and environmental aspects. The originality of this work is presenting a performance model for the novel intermediate pyrolysis and CHP system (hereafter referred as Pyro-CHP), which is developed based on the results from previous experimental work and executed by using the Aspen Plus process simulation software. The energy balance and CHP efficiencies for the engine subsystem and the overall Pyro-CHP system are calculated by the process model for difference system scales. These results of system performance are then utilised in a comprehensive economic evaluation for calculating the Levelised Electricity Cost (LEC) by this integrated system. A sensitivity analysis is performed to examine the impact of aspect range of factors and the optimum LECs are calculated. Finally, the life-cycle GHG emissions associated with operating the system and the total GHG savings available are calculated. The present work is the first time that