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Model based evaluation of six energy integration schemes applied to a small-scale gasification process for power generation

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ABSTRACT

This work considers the use of spent poultry litter as a fuel for on-site power generation. On-site use eliminates the need for the transportation of biomass to centralised plants and the associated bio-security issues. This work utilised process simulation to investigate six process integration schemes applied to a small scale gasification unit with a gas turbine prime mover. The model was used to evaluate schemes involving atmospheric gasification, pressurised gasification and recuperation of energy from the gas turbine exhaust gases. The recuperation of residual heat to preheat air and produced gases was performed with the aim of achieving the highest electrical efficiency. The cold gasification and exergy efficiencies were in the ranges of 58.4–79.5% and 46.8–65.7%, respectively, which mainly increased with increasing ER and then after achieving the maximum value declined. The preferred configuration of the proposed 200-kW process achieved electrical efficiencies between 26% and 33.5%.

1. Introduction

Biomass and agricultural waste used in energy conversion processes has gained attention as a promising alternative to reduce greenhouse gas emissions. Thermochemical processes are preferred since they offer the following advantages: i) the process can be designed to suit on-site application allowing a more compact system, ii) conversion takes shorter times (a matter of minutes) compared to the long periods required in anaerobic digestion, iii) destruction of pathogens due to high process temperatures; the option of employing seasonal residues from farms, and iv) more efficient recovery of nutrients [1]. One thermochemical process is gasification, which converts biomass into a combustible gas mixture by partial oxidation. Gasification is chosen because it solves the problem of waste disposal and represents a viable solution for the on-site generation of energy.

Since the main product of biomass gasification is a valuable mixture of combustible gases, gasification is frequently coupled to power generation systems. Integrated gasification combined cycle (IGCC) puts together a gasification unit and a combined cycle power system. The combined cycle system combines one or several gas turbines (GT) and/or one or several steam turbines which can include a heat recovery steam generator (HRSG). There are currently 18 installed coal-fired plants of large size (200–300 MW) worldwide, mainly located in Japan, the USA, Germany and Holland, which have reached the demonstration stage of commercial-scale IGCC

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plants [2]. Thus, the IGCC technology focuses on high efficiency and large capacity.

Interest on small-scale energy conversion systems using units in the range of 30 kW to 1 MW has recently increased in order to meet a number of local energy and social policy targets, together with the reduction of greenhouse gas emissions [3]. There are some examples of biomass-fired combined heat and power (CHP) plants based on the organic Rankine cycle (ORC) with the size range of 400 kW–1.5 MW demonstrated and commercially available with typical electrical efficiency of ca. 20% [4]. Some manufacturers commercialising ORC modules in the range between 200 kW and 2 MW are Adoratec GmbH, Barber Nichols Inc., Cryostar, GMK, Opcon AB, Ormat Technologies Inc., Pratt & Whitney, TransPacific Energy Inc., Turboden, and WOW Energies. ORC units of up to 250 kW usually use low boiling point hydrocarbons (R-134a, R-245fa, R-152a) as working fluids and give lower electrical efficiencies (8–15%) [5]. However, the implementation of the ORC in small-scale and micro-scale biomass-fired CHP systems faces technical and economic difficulties compared to medium- to large-scale systems. One main barrier is the limited electrical efficiency. A gasification-based CHP system can potentially have higher electricity efficiency than a direct combustion-based CHP system. Talbott's Heating Ltd. has worked on the commercialisation of a biomass combustion-turbine system (100 kW) and reported an electrical efficiency of 17% and overall efficiency of 80–85% [4].

For biomass gasification plants, literature is mostly dedicated to simulation studies.

The understanding of the gasification process allows the operation and optimisation of the system. A useful tool to explore its complexity is the mathematical simulation of the gasification process. Significant work has focused on biomass gasification using chemical equilibrium models [6–10]. The equilibrium calculation provides the final composition and temperature of the product gases considered. Furthermore, equilibrium models are helpful due to the prediction of the thermodynamic limits of the gasification reaction.

Most biomass gasification work has concentrated on wood utilisation. However, the United Kingdom and in general the European Union have large poultry industries that produce 950 and 6800 million birds per year, respectively [11]. From poultry operations, litter is generated as a waste consisting of manure, waste bedding and feathers. In the EU, the litter is removed with every new flock and substituted with fresh bedding material; therefore, an estimated production of 1.4 Tg of poultry litter results from broiler operations [12]. Mortalities are absent from the litter as the checking for, and removal of, casualties from the flock are done on a regular basis (2–3 times a day) and currently regarded as the minimum acceptable level of husbandry. Disposal of poultry litter traditionally includes application to land as fertiliser, but the improper application and overuse of poultry litter represent a potential problem due to: spread of pathogens [13]; emission of ammonia, greenhouse gases and odorous compounds; and ground water pollution through infiltration of nutrients leading to eutrophication [14]. With this growing concern and new regulatory constraints under the provisions of the IPPC directive (Directive 2008/1/EC) [15], land spreading is becoming a less acceptable option. Producers are expected to employ "best available techniques" (BAT) in their waste management in order to comply with this directive. Furthermore, poultry litter represents an available source for energy conversion.

Poultry litter can be a challenging fuel due to its composition; the litter contains bond-nitrogen, sulphur, chlorine and alkalis which when volatilised pose potential harm to further equipment. However, the composition of poultry litter can vary significantly depending on the litter origin and management practices of the farm and the bedding material used. Potassium content has been found very high, with mass fraction of 4–6% (dry basis), when straw was employed. In contrast, a positive effect of alkali metal salts contained in biomass ash, especially those containing potassium, is the promotion of gasification reactions; an almost eight-fold increase in co-gasification rate at 1168 K was observed in a 10:90 mixture by mass of coal char and switchgrass ash [16]. Tar reduction has also been achieved by using alkalis. When wood was impregnated with potassium carbonate during steam gasification, phenolic tar compounds were reduced by a factor of five and PAH by ten, and furans and ketones were also significantly reduced [17]. Gas-phase concentration of alkali constitutes and low melting temperature of alkali ash components can cause ash deposit formation and agglomeration. However, experiments of chicken litter ashes showed no clear melting point in the range of temperature analysed (up to 1873 K) [18], and the initial deformation temperature and fusion temperature were measured as 1412 and 1436 K, respectively [19]. Trace elements, such as arsenic, could also be of concern. For that reason, growth stimulants containing arsenic (e.g. Roxarsone (3-nitro-4-hydroxyphenylarsonic acid)) were banned in the UK. Because arsenic is not included in the poultry diet, as might be present in an insignificant amount in the litter [20].

Most systems use the hot gas turbine exhaust gases essentially to generate steam. However, electricity production could be maximised by avoiding the generation of steam and the cost of an HRSG unit. The hot gases from the GT can be used as a heat source for the biomass gasification process as it is proposed. The main objective of this work is the simulation of the gasification of poultry litter integrated with a gas turbine using a small-scale and on-site system. In addition, residual heat is recuperated to preheat air and product gases in order to achieve the highest electrical efficiency. An equilibrium model is used to compare and evaluate six integration schemes of a 200 kW unit. Despite inorganic species were considered and included in the simulation, this work does not show the results of the partition of alkalis or the formation of NO_x and SO_x; no attempt to include minor products such as tars was done.

2. Method

2.1. Process configurations

In order to compare the performance of the proposed pressurised system, this was compared to a conventional arrangement using an atmospheric gasifier. In addition, four more arrangements that include heat recovery were analysed. Therefore, six case studies were evaluated as explained below.