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Thermal Conversion of Biomass and Waste

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Thermal conversion of biomass and waste

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ABSTRACT

This paper investigates the process designs of 2 fluidized bed gasification plants utilizing clean biomass. Energy and mass balances for each process were carried out and ChemCAD was used to evaluate the energy recovery process by simulating the operation of a steam turbine and a combined cycle gas turbine (CCGT).

INTRODUCTION

In the developed world, 75% of the population live in urban areas, a figure projected to rise to nearly 83% by 2030, while in the developing world, this rate of urbanisation is even faster. One of the most important environmental problems associated with urbanisation is the amount of waste that is generated at a rate that outstrips the ability of the natural environment to assimilate it and authorities to manage it (1).

Therefore, if we are to deliver a more sustainable economy, we must do more with less by optimizing the recovery of resources from waste, whether as materials through recycling and composting or as energy or fuel through efficient biological and thermal processes. The use biomass and waste to produce energy or fuel is not only an important waste treatment option but it also can:

- reduce UK's reliance on landfill and cut volumes of biodegradable municipal waste landfilled to 75%, 50% and 35% of the 1995 levels by 2010, 2013 and 2020, respectively;
- meeting the UK's target of 10% power generation from renewables sources by 2010;
- achieving Kyoto Protocol commitments in reducing greenhouse gas emissions.

The work reported this paper is part of the research programme of Engineering and Physical Sciences Research Council (EPSRC), Sustainable Urban Environment (SUE) Waste Management Consortium. The work investigates the appropriate scales and technologies for the production of energy from waste in the urban environment in relation to sustainable waste management. The suitability and effectiveness of a variety of fluidized bed combustion and gasification technologies are assessed, together with gas clean-up processes. The most appropriate scales for each of these approaches in relation to thermal efficiencies and costs are being assessed so that a sound judgment can be made as to which processes should be used in the urban context.

BIOMASS GASIFICATION

The process designs of 2 fluidized bed gasification plants were studied. The first plant was designed by Germanà & Partners Consulting Engineers in collaboration with ENEA (The Italian National Agency for New technologies, Energy and Environment) and the Liaoning Research Institute of Yingkou in China. The plant employs an internally bubbling fluidized bed gasifier. The second plant was developed by University College London (UK) in collaboration with University of L'Aquila (Italy) and commissioned by the Energy Department of the European Commission and Ansaldo CLC. It employs a circulating fluidized bed gasifier.

Both projects were aimed at performing research and technical development of fluidized bed gasification and the generation of heat and power from renewable sources, i.e. biomass. The work is also aimed at addressing the perceived risks associated with the development of renewable energy technologies as both projects proved their technical feasibility. The first plant has the advantage of using an interconnected fluidized bed gasifier, which divides the vessel into two zones. This enhances the solid-gas mixing, reduces fine particle elutriation and subsequently results in increased system efficiency.

The second plant was aimed at the production of hydrogen-rich gas by biomass gasification and coupling the process with fuel cells in an integrated system for decentralized heat and power generation. Hydrogen is an energy-efficient, low-polluting fuel and is considered as one of the most promising energy carriers for the future. Coupling of biomass gasification with fuel cells offer an economically attractive market for dedicated energy crops, which can help overcome the high investment capital associated with fuel cells.

Both projects are also suitable as rural energy systems. Gas engines, as utilized by the first plant, are widely used in rural areas and present the most economical options for electricity generation (2). They have efficiencies of around 20%. Fuel cells on the other hand, have high recoded efficiencies in the range of 40-60% and extremely low emission levels. They are available in small modular units with power capacities ranging from 0.01-0.25 MWe and therefore can be easily integrated into small to medium-scale energy systems.

Small-scale biomass electricity generation plants can also be fuelled by local resources, which can reduce the economic difficulties of transporting bulky fuels with low calorific values over large distances. The electricity generated can be sold locally or consumed internally, while the heat produced can be utilized within the process.

Bubbling fluid bed

The plant uses a bubbling fluidized bed reactor, which utilizes Chinese wood to generate 160 kW of electricity using an electro-generator (an internal combustion engine). A schematic diagram of the process is shown in Figure 1. The gas cleaning system of the plant comprises of a cyclone and a scrubber. The cyclone removes the solid particulates while the scrubber removes tar and other gaseous pollutants.

The gasifier has a novel design structure, in that it is divided by a baffle plate into two zones. Biomass is introduced into the main, dense zone of the gasifier and material circulation takes place between the two zones.

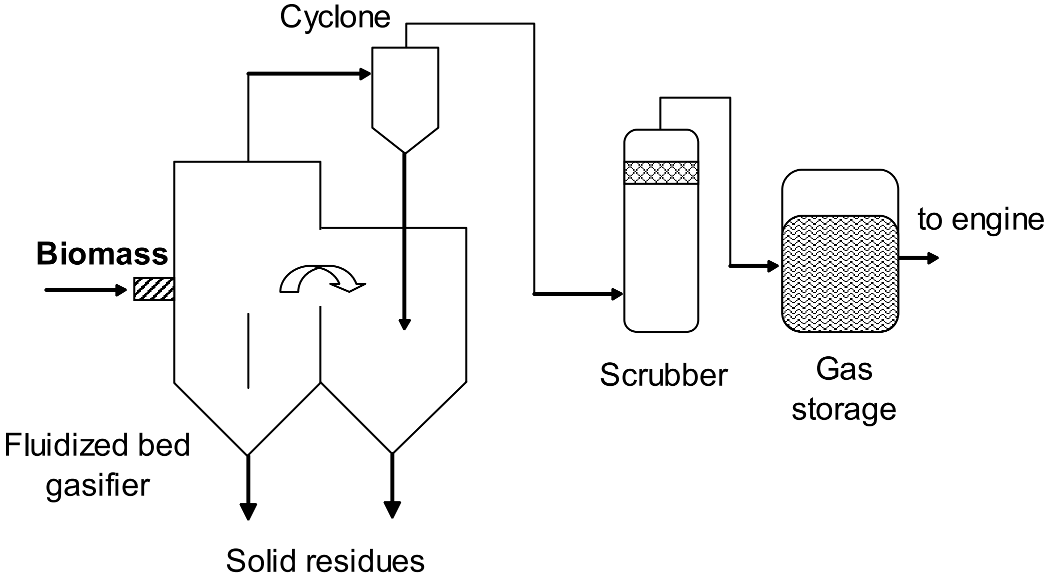

Figure 1. A bubbling fluidized bed gasification process

Kuramoto et al. (1985) and (1986) have studied the circulation of dense fluidized particles in 2D and 3D beds as illustrated in Figure 2. For the 2D bed, the reactor was divided by a partition plate with an opening to form two portions of fluidized beds with different gas velocities (3). For the 3D bed, the interior of the vessel was divided into four sections by intersecting two flat vertical plates at right angles. Two sections were used for the up-flowing bubbling fluidized beds and the other two sections were used for the down-flowing bubble-free fluidized beds (4).

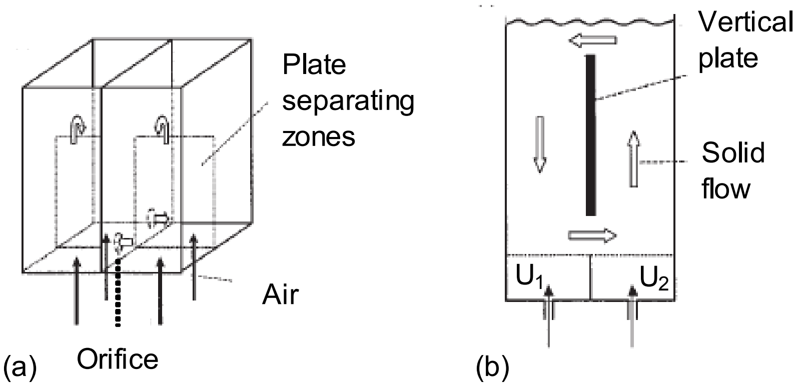

Figure 2. Interconnected fluidized bed reactors: (a) Four zones of fluidized beds and (b) Two zones of fluidized beds

The particle circulation between the zones was attributed to the difference in the fluidizing gas velocities and the pressure drop across the orifice. This pressure drop is directly proportional to the difference in the average density of the interconnected fluidized bed system and its height. Particle segregation is a common drawback in most biomass fluidized bed applications. It arises because of the differences in size and density of the particles leading to a variation in particle concentration over the bed height (5). Particle circulation between zones in interconnected fluidized beds eliminates this drawback as it enhances the gas-solid mixing and therefore preventing segregation from taking place.

Mass and energy balances

The proximate and ultimate analysis of the biomass is summarized in Table 1. The proximate analysis shows the contents of fixed carbon, moisture, volatiles and inerts as well as the lower heating value (LHV) of the biomass. The ultimate analysis gives the elemental compositions of the biomass in dry wt% of carbon, hydrogen and oxygen and nitrogen.

Table 1. Proximate and ultimate analysis of the biomass used

Proximate Analysis					**Ultimate Analysis**			
Fixed carbon	Moisture	Volatiles	Inerts	LHV	C	H	O	N
%	%	%	%	kcal/kg	%	%	%	%
8.37	31.94	83.44	1.86	4418	48.21	6.43	45.13	0.23

Mass and energy balances of the gasification process were carried out based on these compositions and the results are shown in Figure 3. The plant utilizes 280 kg/h of Chinese wood and generates 160 kW of electricity using two Fiat gas engines, each with a nominal power of 80 kWe. The engine has an efficiency of 22% while the generator has an efficiency of 90%, giving an overall energy conversion efficiency of 20%.

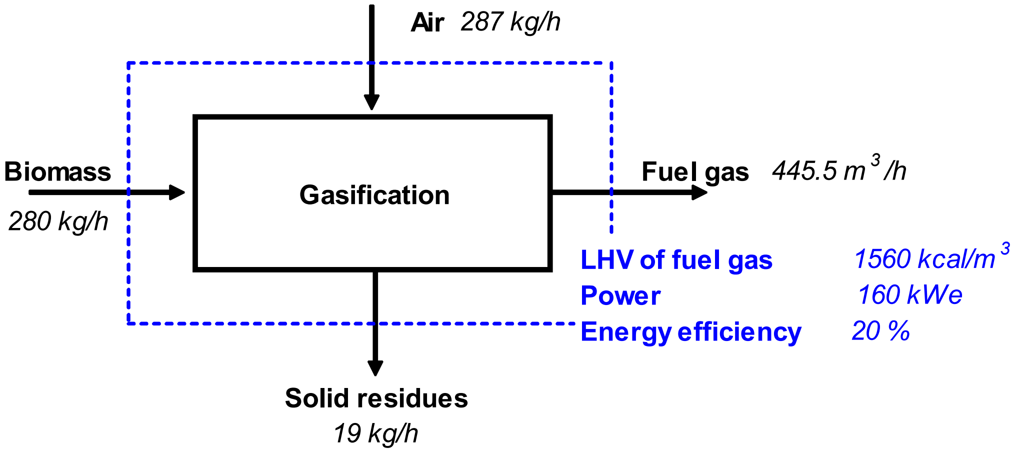

Figure 3. Mass and energy balance of the gasification process

Circulating fluid bed

The plant uses a circulating fluidized bed reactor, shown in Figure 4, to gasify clean wood and generate 914 kW of electricity using a phosphoric acid fuel cell (PAFC). It also incorporates an extensive gas cleaning system. Phosphoric acid fuel cells are commercially available and operate on natural gas and air. They can be easily integrated into the gasification system and have electrical generation efficiency of typically 35%.

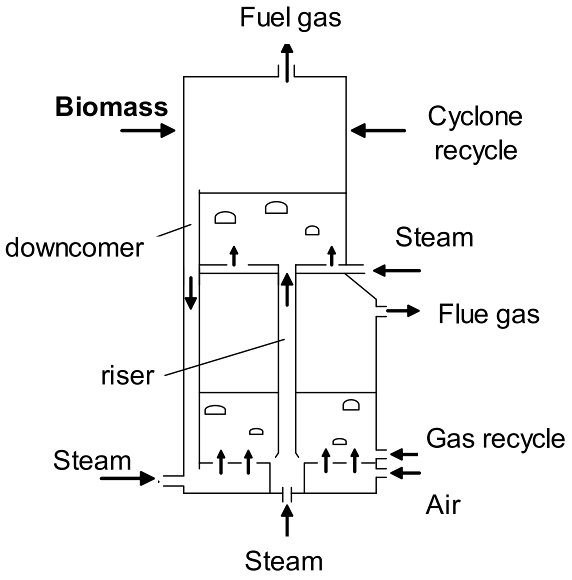

Figure 4. A circulating fluidized bed gasifier

In this gasifier configuration, the fuel gas exits at the top while the solids (char & ash) fall through the down-comer to the combustion section. Sand is used as an energy carrier supplying heat produced from the combustion section to the endothermic gasification reaction. The downstream gas clean-up system of the plant, shown in Figure 5, consists of:

- cyclones to separate solid particles from gas;
- catalytic reformers to remove hydrocarbons like tar and CH_4;
- a scrubber to remove dust and acidic components such as chlorides and fluorides;
- desulfurizers to remove any remaining S-compounds such as H_2S;
- a two-stage water-gas shift reactor system to convert carbon monoxide to hydrogen and carbon dioxide.

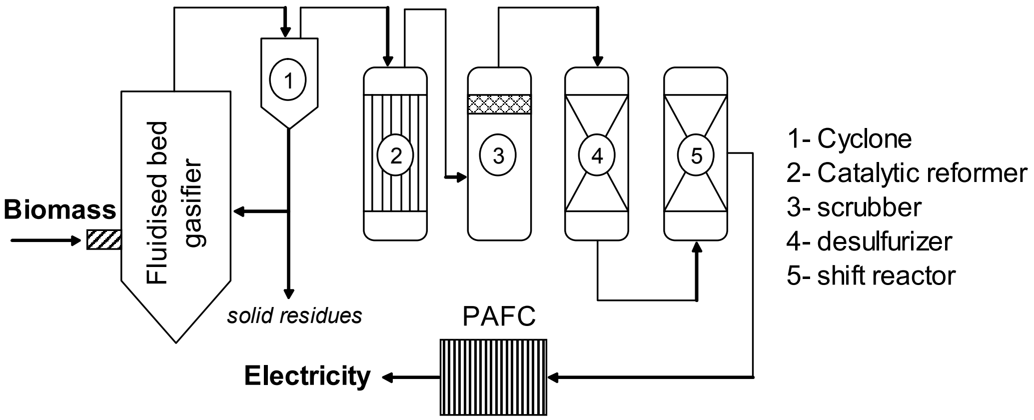

Figure 5. Simplified schematic diagram of the plant

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Mass and energy balances

The proximate and ultimate analysis of the biomass used in this plant is summarized in Table 2. Mass and energy balances of the gasification process were then carried out based on these compositions and the results are shown in Figure 6.

Table 2. Proximate and ultimate analysis of the biomass used

Proximate Analysis					**Ultimate Analysis**			
Fixed carbon	Moisture	Volatiles	Inerts	LHV	C	H	O	N
%	%	%	%	kcal/kg	%	%	%	%
18	20	56	6	4181	48.65	5.4	44.59	1.15

The plant utilizes 732 kg/h of clean biomass and produces a hydrogen-rich fuel gas comprising of over 66% H_2 on a dry mol basis. 81.7% of the H_2 is consumed by the PAFC to generate 914 kW of electricity. The plant also co-generates 744 kg/h of steam at 140°C and 3.7 bars. The thermodynamic efficiency of the process using PAFC is 44%, however, the net electricity conversion efficiency is above 30% (6).

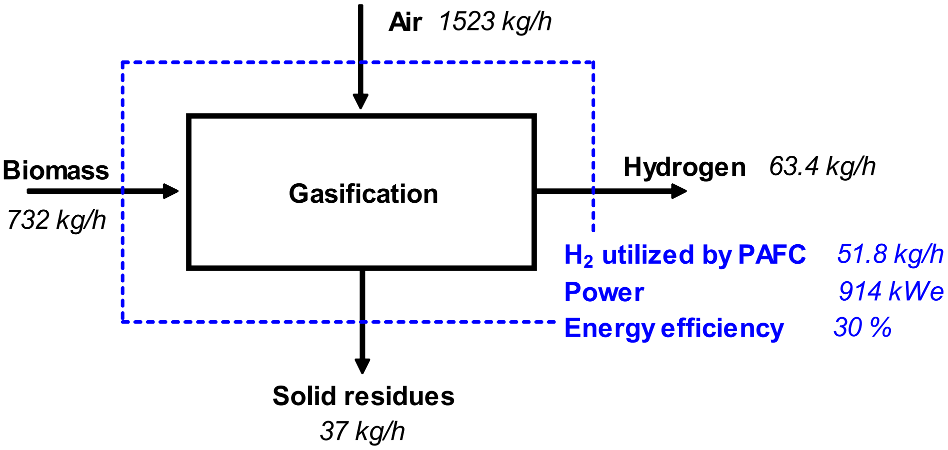

Figure 6. Mass and energy balance of the gasification process

ENERGY RECOVERY OPTIONS

Having studied the process design of the fluidized bed gasification processes using a gas engine and a phosphoric acid fuel cell, the efficiency of energy recovery using a steam turbine and a combined cycle gas turbine (CCGT) is currently being investigated.

In a gasification process, the fuel gas can be combusted in a gas turbine to produce electricity. The resulting hot exit gas from the turbine still has significant amounts of energy, which, in turn, is used to raise steam to drive a steam-turbine and produce more electricity. This combination of a gas and steam cycle is known as a combined cycle gas turbine. In a combustion process, the steam generated from burning the biomass or waste can only be used to generate power or heat by using a steam turbine. Therefore, the increased utilization of energy by CCGT units improves the efficiency of energy recovery.

The operation of a steam turbine and CCGT was modeled using ChemCAD to compare the energy recovery efficiencies of the different thermal conversion processes, namely combustion and gasification. A ChemCAD simulation for a CCGT unit generating 22 MWe from a 4 t/h of syngas at 20°C and 3.5 bars is demonstrated in Figure 7.

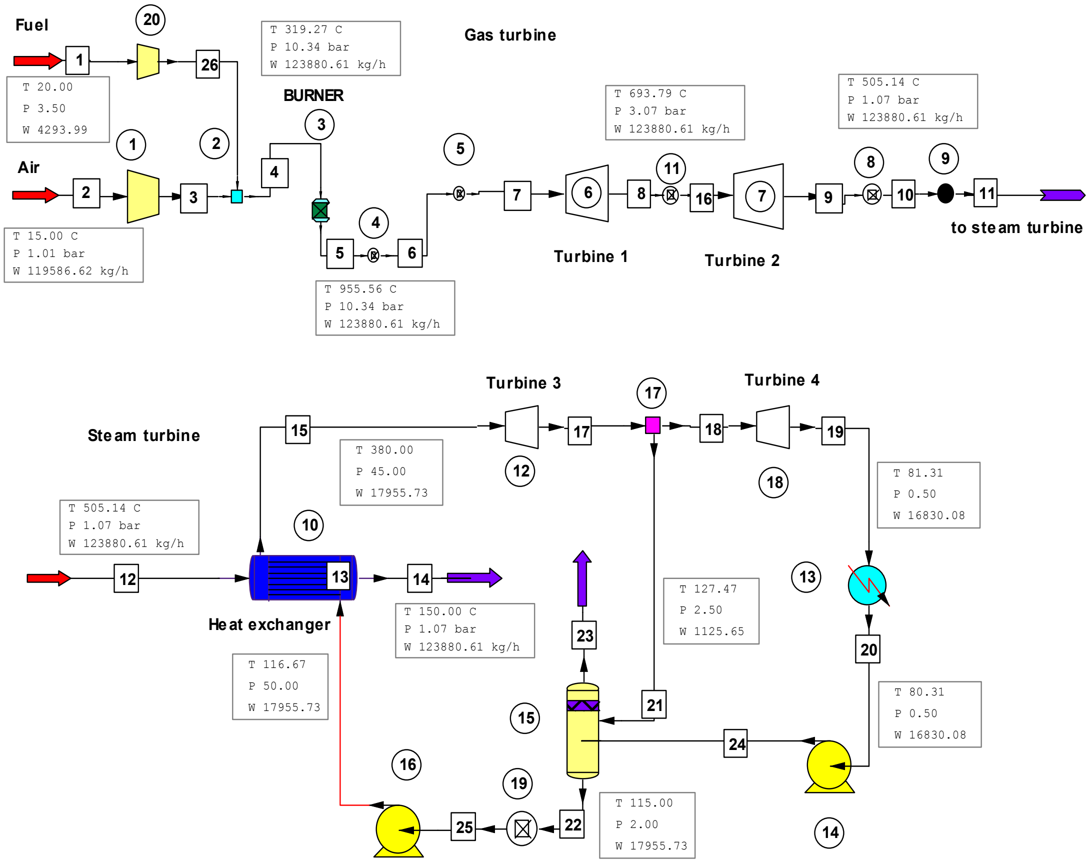

Figure 7. A ChemCAD flowsheet for a CCGT unit test simulation

CONCLUSION

The process design of 2 fluidized bed gasification plants were studied as part of the current work on appropriate scales and technologies for energy recovery from waste by combustion and gasification. The overall aim of the study is to assess the suitability and effectiveness of a variety of fluidized bed technologies in relation to thermal efficiencies, environmental impact and economics, so that a sound judgement can be made as to which processes should be used in the urban context.

Energy and mass balances for each process were carried out and ChemCAD was used to evaluate the energy recovery process by simulating the operation of a steam turbine and a combined cycle gas turbine.

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