DEVELOPMENT OF A SMALL-SCALE

BIOMASS CHP SYSTEM

ETSU B/U1/00678/REP

DTI/Pub URN 02/681

Contractor
Sustainable Energy Ltd.

Prepared by
Dr G J Gallagher

The work described in this report was carried out under contract as part of the DTI Sustainable Energy Programmes The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI.

First published 2002

Executive Summary

Sustainable Energy Ltd (SE) initiated their biomass research programme with a project funded by the SMART Award scheme to develop a small scale pyrolyser based on cyclonic flow. Stemming from work on this project and a working relationship with Cardiff University the concept of biomass gasification for CHP generation was born. Bringing together fundamentals of SE pyrolyser and findings from a biomass gasifier developed at Cardiff University resulted in the concept of the swirl flow gasifier CHP system.

The objectives of this project were successfully met by demonstrating a novel prototype small-scale biomass CHP system. A compact biomass gasifier adopting swirling flow to incorporate particle separation within the reaction produced wood gas to fuel a CHP engine with minimal post processing equipment for gas cleaning. The technical objectives were devised to reduce capital equipment costs of biomass CHP systems and thus to enhance the economics of small-scale biomass heat and power projects using this technology.

With worldwide commitment to reduce CO_2 emissions and increase the amount of electricity generated by renewable resources, bioenergy is predicted to provide a major contribution to our future energy mix. Biomass is also being seen to offer rural regeneration and permanent job creation in the biomass supply sectors. However, the low energy density of raw biomass resource means much higher levels of transportation are required to move fuel to sites of use, therefore larger power stations that consume biomass from wide areas will induce pressures on rural infrastructure, namely roads. Small-scale biomass systems for on-site generation sited within small catchment areas of biomass resource should prove favourable due to significantly lower impact on local surroundings.

This project developed a small-scale biomass system to convert biomass in the form of sawdust into electricity and heat. The project focused around a swirling flow gasifier, which was driven by air injected at atmospheric pressure conditions. The gasifier was sized to process 40kg/hr of sawdust and generate 45kW of electricity and 100kW of heat. The swirling flow within the gasifier incorporated two stages of particle separation in a rapid entrained flow reaction. The result was a low calorific value wood gas of low tar and particle content. The system included further gas cleaning to separate any fine ash particles, moisture and tars from the wood gas before firing a diesel Internal Combustion (IC) engine converted to spark ignition.

The gasifier was successfully tested at biomass feedrates of 40kg/hr, however due to problems with the 45kWe CHP engine the gasification system was demonstrated using a smaller 12.5kWe IC engine with the gasifier turned down to 50%. At 20kg/hr the gasifier produced 73kW of wood gas, of this 33kW was used to feed the IC engine and generate 10kW of electricity, the remaining 40kW was flared off. The gasification efficiency was calculated to be 75%, which subject to the amount of wood gas used to power the IC engine

gave a total electrical conversion efficiency of 22.7% (wood in to electricity out) and a wood gas to electrical efficiency of 30%. Several hours of operation were achieved with the engine running on wood gas but within the scope of the project the assessment of the long-term effects of wood gas on the engine was not carried out. The research and development aims were completed successfully with a wood gas of calorific value 5.7MJ/kg produced which proved suitable for fuelling a CHP engine.

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1 Introduction

Reducing the emission of carbon dioxide (CO_2) and other greenhouse gases is one of the greatest environmental challenges of our time. In general, mankind has accepted the damaging effects of global warming (and its link to greenhouse gases) caused by our reliance on fossil fuels. In light of this, the European Union has undertaken a commitment to reduce CO_2 emissions by 8% by 2012 (base line 1990).

The European Commission Renewable Energy White Paper prescribes to generating 12% of the total European electricity demand by renewable sources by 2010, this represents a doubling of generation. The challenge is even greater for the UK where current renewable energy generation is approximately 2.9% compared to the UK's targets of 10% by 2010. Biomass is predicted to play a major role within the portfolio of renewable energy sources that will be exploited to help meet these targets. Some studies have predicted that bioenergy will provide up to 70% of this total renewable energy generation.

Biomass heat and/or power generation using new state-of–the-art technology is fast becoming an economic and environmentally viable method of energy production. The global market for the provision of bioenergy goods and services is already growing rapidly and is estimated to be worth at least £30 billion p.a. within 5 years. Indeed the UK government anticipates that the UK market will be worth £1 billion p.a. by 2010.

Biomass resource is extensive, with fuels such as forestry residues, energy crops, manufacturing wood wastes, olive husks, bagasse from the sugarcane process, grasses, livestock residues (cattle, pigs and poultry) and food processing residues all having been used for energy generation.

Biomass gasification, the complete conversion of biomass to a gaseous fuel by heating it with a gasification medium such as air, oxygen or steam is fast becoming the most promising process for electricity generation. Biomass gasification products have been demonstrated for the generation of electricity via boilers and steam turbines, internal combustion engines, fired in gas turbines and even proven suitable for some types of fuel cell.

Woody biomass maintains net calorific values between 18MJ/kg and 19.5MJ/kg, this is almost half that of natural gas and fuel oil. This coupled with the low mass density of biomass means biomass has a low energy density compared to fossil fuels and therefore higher levels of transport present barriers to large-scale plants.

1.1 Small-scale biomass CHP

Although biomass is seen to play a significant part in our future energy mix, there are impacts and barriers to the uptake of large biomass energy generation projects:

Transport of large quantities of biomass fuels from source (often rural forestry) to the site of use is one of the major obstacles to the development of larger biomass plants as the low energy density of wood fuel leads to increased levels and cost of transportation. Small-scale biomass electricity generation means plants can be fuelled by local resource from small adjacent catchment areas.

Emissions of CO_2 are neutral and sulphur oxide emissions are low. Whilst nitrous oxides and particulate emissions must be kept within limits for large biomass plant, smaller plant will avoid this tight legislation set for large scale power generation.

Electricity costs for biomass electricity generation are currently higher than the effective price for renewable energy electricity proposed to be set by the UK government through the Renewable Obligation (RO). This coupled with the high installation costs means that current economics are a constraint to biomass development. Overcoming this constraint will require either significant financial incentives or reduction in capital costs of biomass plant.

Current small-scale biomass technology such as the relatively inefficient combustion technology or expensive downdraught gasification systems has to date restricted the development of small-scale biomass energy projects. Therefore technological advances, which will improve system efficiencies and reduce capital cost, manpower and maintenance requirements, will allow biomass generation to become economically viable.

Approximate costs capital equipment and costs for generation of electricity from biomass are shown below in Table 1:

Table 1 Cost of biomass electricity generation

Energy Output	Conversion Technology	Cost per kW Installed
Electricity	Combustion (<500kW)	£2,000
Electricity	Gasification	£1,500
Electricity	Steam/Gas (Large Scale)	£1,200

1.2 Objectives

The objective of this project was to develop and demonstrate a compact entrained flow biomass gasifier using a swirling flow reactor to suspend and react pulverised biomass into a low tar and particle content wood gas suitable for fuelling a CHP engine with minimal post processing equipment for gas cleaning.

The technical objectives were designed to achieve a significant reduction of capital equipment costs, thus enhancing the economics of small-scale biomass heat and power projects using this technology compared with other commercial biomass gasifiers.

2 Review of biomass gasification for small-scale CHP

2.1 Biomass gasification

Biomass gasification technologies are generally at an early stage of development compared to coal gasification systems. While some biomass gasifiers have been demonstrated commercially, most are still in the development or early demonstration process. Of the small number of commercially viable systems in operation there are only a few systems that have been economically demonstrated at a small-scale.

There are five main gasification technologies, each having varying suitability for small-scale applications of driving engines, turbines or firing in boilers. The different configurations of systems currently being developed are summarised briefly as follows:

2.1.1 Fixed bed gasifiers

Fixed bed gasifiers pass the gasification medium (air/oxygen/steam) through a hot bed of biomass. There are two main variations of the fixed bed gasifier: the up-draught and down-draught. Other variations of the fixed bed system such as the cross-draught gasifier exist but have little operational experience and again are restricted in size.

2.1.2 Up-draught

The up-draught process introduces the air from below the bed, this process produces high levels of tar, thus the wood gas requires significant cleaning before use with internal combustion engines.

2.1.3 Down-draught

Down-draught gasifiers produce gases of much lower tar contents, thus making themselves more suitable for power generation with engines, however, there are problems with scaling up above 1MW as non-uniform bed temperatures reduce the efficiency of the process. This process has been most often used for small-scale commercial applications running IC engines for biomass electricity generation.

2.1.4 Fluidised bed gasifiers

Fluidised bed gasifiers consist of biomass fed into the system and fired from below with air to gasify the biomass while in suspension and reaction. The advantages over fixed bed systems are the more uniform temperatures in the gasification zone. Bed material such as dolomite can be used for catalytic cracking of the tars. The main disadvantage is the sintering of the bed material caused by ash and alkali content in the biomass and therefore must be removed. Most large commercial gasification plants have been based on this fluidised bed gasification process.

2.1.5 Bubbling bed gasifiers

Bubbling bed gasifiers consist of a vessel with a grate at the bottom, through which air is introduced. Above the grate there is a moving bed of fluidising material (ash) into which the biomass is fed. The air-feed rates are low, so that the bed material doesn't leave the reactor with the product gas. These bubbling bed gasifiers produce low tar contents, can be successfully scaled up and have good tolerance to feed quality and moisture content.

2.1.6 Circulating fluidised bed gasifiers

Circulating fluidised bed gasifiers use higher air velocities than the bubbling bed system to entrain the fluidising material and char through the reactor into the cyclone separator and back to the bed. High capacities can be reacted, thus it is applicable for large plants of up to 20MWe.

2.1.7 Entrained flow gasification

Entrained flow gasification involves the entrainment of small biomass particles such as sawdust or wood powder in air with gasification occurring during the partial combustion of the fuel. This process produces low tar gases and can be controlled more directly as the biomass particles and air pass rapidly through the reactor. Commercial experience is limited, however systems such as cyclonic gasifiers have being developed for gas turbine integration.

2.2 Wood gas characteristics

The gas quality produced by different gasification processes is affected by the gasification medium, which can be oxygen, air or steam. As gasification with pure oxygen is expensive, air is more commonly used. Due to the high content of nitrogen this reduces the calorific value of the produced gas. For example, gasification with air produces a gas with a Lower Calorific Value (LCV) of 4 – 6MJ/kg, whereas gasification with oxygen produces a gas with a LCV of 10 – 15MJ/kg.

Typical volumetric fractions of the gases found in wood gasified in air are listed as in Table 2.

Table 2 Typical gas composition of wood gasified in air

Gas	% v/v
CO	19 – 25
H_2	9.5 – 11.5
C_xH_y	1.5 – 2.0
CO_2	14.4 – 16
N_2	45 – 55
O_2	2.5 – 4

The LCV for each of the combustible gases found with in the wood gas are listed in Table 3.

Table 3 Lower Calorific Values of combustible gases

Gas	LCV (MJ/kg)
CO	11.97
H_2	10.22
CH_4	33.95
C_2H_6	60.43

Therefore a typical wood gas as shown in Table 2 would have the LCV of 4.6MJ/m^3. This compares rather unfavourably to the LCV of natural gas or diesel, which are generally the fuels used for non-biomass CHP systems. Wood gas invariably contains other contaminants such as tar, char and ash particles and alkali salts, which can cause wear, contamination and build up on surfaces and moving parts. Gas cleaning and / or modifications to CHP engines are therefore required to enable these systems to be run on wood gas.

2.3 Biomass Combined Heat and Power (CHP)

To generate electricity and heat from the biomass gasification wood gas, prime mover technology such as heat engines, internal combustion engines and micro gas turbines can provide the mechanical shaft power to drive an alternator for electricity generation with recuperation of heat energy from the exhaust gas for heat generation.

Heat engines such as the Stirling engine can be used by indirectly firing the gas through the engine. The advantage is that all moving parts are not in contact with the tar, particles and alkali salts commonly found in the wood gas. The down side is very low electrical efficiencies currently achievable with these technologies.

Wood gas is well suited to CHP applications using internal combustion (IC) engines. Biomass CHP engines can be diesel engines run with a small percentage of pilot liquid fuel such as diesel. Alternatively, diesel engines converted to spark ignition can be run solely on low/medium calorific wood gas. IC engines can typically provide 24% to 30% electricity and up to 60% heat. The wood gas impurities, tar, particulates, nitrogen compounds, sulphur compounds and alkali compounds can cause various problems such as tars sticking to internal surfaces, particulates causing blocking and corrosion caused by alkali content. The use of wood gas in IC engines therefore requires significant gas cleaning.

The micro gas turbine can also be used effectively with atmospheric or pressurised gasification systems, which due to the high velocity flows are less affected by sticking tar and particulates. Another advantage of the gas turbine is the outlet gas has much higher temperatures leading to better thermal efficiency of the system. However, existing small gas turbines have lower electrical efficiency with only up to 20% of the input energy available at the shaft. Further efficiency can be achieved with a combined cycle utilising a bottoming steam cycle. As the current state of turbine technology is focused on larger systems, modern efficient small-scale gas turbines are either not yet suitable for wood gas or have lower electrical efficiencies of less than 20%.

3 Gasifier / CHP design criteria and calculations

3.1 Gasifier air/wood ratio

For an entrained gasification system it is important to maintain accurate continuous air/wood ratios to ensure a steady reaction and optimum calorific value of the wood gas produced. The air/wood ratio range within gasification is to be maintained lies between the theoretical ratio (calculated from a global chemical reaction) and ideal ratio as shown below in Table 4.

Table 4 Air / fuel ratio for gasification

	Combustion	Theoretical gasification	Ideal gasification
Equivalence ratio	1	0.43	0.19
Air/wood ratio (kg air/kg biomass)	6.26	2.69	1.19

The air / wood ratio will be factored into the design of the biomass feeder system and reactor inlet geometry as sufficient transport air velocities are required to carry the sawdust particles into the swirling reaction zone.

4 Experimental equipment and techniques

4.1 Prototype experimental rig

The prototype small-scale biomass CHP system comprised a wood feed hopper and feed auger, air blower, cyclonic gasifier, external cyclone, cooler/condenser and engine. The rig is shown below Figure 1 with Figure 2 presenting a simplified diagram.

Figure 1 Prototype rig – wood feeder, gasifier, gas cleaning and engine

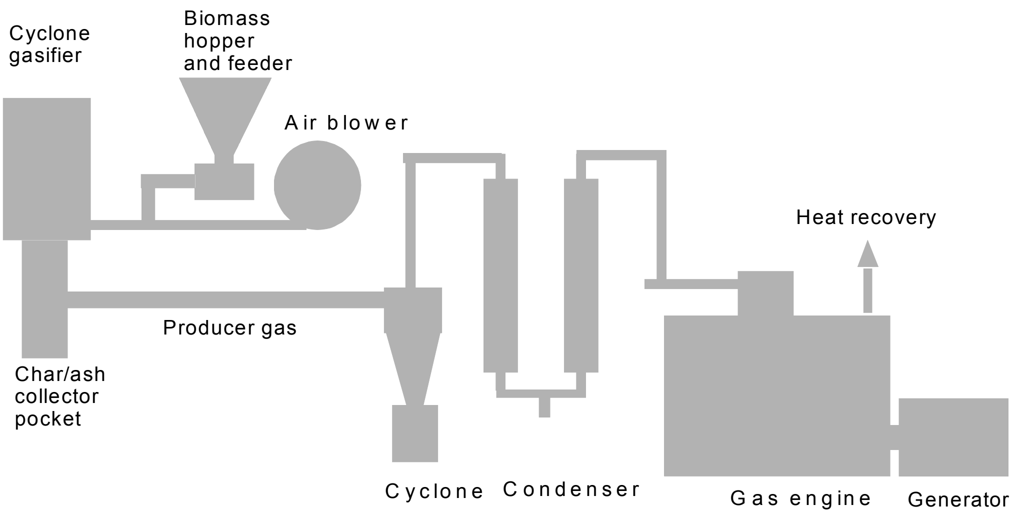


Figure 2 Schematic of experimental set up

4.2 Biomass gasifier

The biomass gasification system developed within this project was a swirling flow gasifier. The concept of this entrained flow gasifier used air to entrain wood powder (in the form of sawdust) in a turbulent vortex within the reactor, which incorporated two stages of separation to remove the char and ash produced in the process. The intense continuous reaction enabled gasification of high volumes of biomass in the compact reactor.

The system used for this work was sized to gasify up to 40kg/hr of sawdust under atmospheric pressure conditions, this gives a total energy input to the gasifier of around 190kW. The system was tested over a range fuel input rates from 20kg/hr up to 40kg/hr. For the final testing with engine operation the gasifier was turned down to half its peak capacity of 20kg/hr, results shown in this report reflect the performance of the gasifier in turn down operation.

The various initial reactor designs were manufactured from mild steel and were soon life expired under the high temperature test conditions. The final prototype gasifier was manufactured in 316 grade stainless steel and proved suitable when tested under continuous high temperature (900°C max) operation conditions. Figure 3 shows the reactor without outer insulation.

Figure 3 Cyclone gasifier without insulation and outer jacket

To give a perspective of the compact design discussed in this report, a typical fixed bed gasifier of same capacity would be a factor of 20 to 30 times larger in volume than the gasifier developed within this project. The internal characteristics and geometry remain intellectual property of Sustainable Energy Ltd. and therefore are not detailed within this report.

4.3 Development

As mentioned earlier, the major focus of the project was development of the gasifier. Iterations of design, manufacture and testing were numerous to achieve the optimum reactor design and geometry to entrain the biomass particles in a swirling air flow while ensuring sufficient reaction time for gasification to occur. The wood particle entrainment was limited by the tight limits set for the wood/air ratios.

4.3.1 Isothermal particle flow testing

Of prime importance was the flow dynamics and particle trajectories within the reactor, therefore a study under isothermal conditions was carried out to visually observe the path and time the biomass particles took within the flow. Sawdust particles were used to determine the initial particle flow, maintaining particle velocity and direction without dropping out from the primary flow. Ash and char particles were used to determine the characteristics of the up stream particle separation. Cold air flow rates were adjusted to simulate hot flow conditions. The slow shutter speed of the digital camera meant that recording the particle dynamics was not possible in the scope of this project and as such, the work was recorded by manual observation.

4.3.2 Heat-up gas burner

A burner system was designed to supply and ignite a supplementary gas to fire through the gasifier to heat it up to temperatures to initiate gasification reaction. Specification temperatures were up to 800^{o}C for the reaction initiation. The design also ensured no interruption of the gasification reaction and not be fouled by biomass particles.

4.4 Hopper/feeder system

The biomass hopper and feed system consisted a small hopper with agitator and single horizontal auger screw, which fed the sawdust into an airflow driven by a high-pressure centrifugal fan. The centrifugal fan was driven by a 3 phase 3kW motor, the continuous operational requirement for this fan was approximately 1kW. In practice the blower would be connected directly to the engine shaft and therefore calculated to require less than 750W of mechanical power from the engine. The screw was an increasing pitch auger screw which was driven by a variable speed motor. The hopper was small, however provided sawdust loading of 20kg of feedstock, which under most test conditions was suitable but needed refilling for longer tests. The hopper, screw and fan wood/air feed system is shown in

Figure 4 below.

Figure 4 Sawdust hopper and feeder system

4.5 Cyclone

An external high efficiency cyclone was fitted within the prototype system for evaluation of the separation characteristics of the gasifier. Once the cyclone gasifier was optimised for particle separation the cyclone could be removed or replaced by a filter further down stream. Removal of cyclone would reduce the pressure drop over the system and thus reduce the energy required from the air blower.

4.6 Cooler/condenser

An array of 'U' tube design condensers were used to cool the wood gas and condense any water and tars from the gas. The cooler was designed to reduce wood gas from temperatures of ~ 700 ^oC – 800^oC down to ~ 30 ^oC - 40 ^oC, so that the maximum volumetric energy content of the wood gas is achieved. The design factored in minimum pressure drop across the system.

4.7 Filter

The cool gas was filtered in various filter systems such as in line fibre filters and oil bath filters to evaluate the performance of the upstream separation systems.

4.8 CHP engine

A 6-cylinder Ford spark ignition 45kWe CHP engine was first installed for the test programme, however problems with the engine ignition timing system discovered late in the project meant a replacement smaller Lister spark ignition diesel engine fitted with a 12.5KVA generator was used to carry out the engine operation analysis. Time and budgetary constraints meant that the 45kWe CHP engine was not reconnected to the system.

4.8.1 Carburettor

Due to the high low air to fuel ratio required to form a combustible gas, the carburettor was removed and a simple gas mixing configuration was used to replace it. The wood gas / air ratio was created by adjustment of two rotameters shown in Figure 5.

Figure 5 Test engine configuration

4.9 Alternator

The alternator was a 3 phase 400V 1500 rpm rated at 12kVA.

4.10 Control system

Within this development project there was no requirement for a full control system as all parameters could be adjusted manually during operation. The stability of the gasification reaction meant that once air and wood feed rates were set, the reaction would continue within a close tolerance. Engine operation was controlled by a engine governor once air / gas ratio's were set manually.

A control system for complete automated operation was kept in mind when designing this biomass CHP system; this will be developed under future development work.

4.11 Measurement techniques

4.11.1 Temperature

Temperature was measured in various positions along the process by 'k'-type thermocouples and read with digital displays. As the majority of the work was system development, data acquisition was carried out by manually recording system temperature.

4.11.2 Volumetric air/gas flow and velocity measurement

Generally, all 'cold' flows, such as start up gas, gasifier air, engine air and cold wood gas engine inlet were measured by in line rotameters. Variations due to temperature, gas composition and pressure were taken into account for measurement of wood gas input to engine.

4.11.3 Pressure

Pressure sensors were used to analyse the pressure drops induced by gasifier design changes, and gas process cleaning and cooling.

4.11.4 Gas analysis

Wood gas composition was measured using a Testotherm gas analyser.

4.12 Experimental procedure

The major part of the development work focused on the gasifier with variation of geometric parameters of reactor height, diameter, inlet area, collection pocket placement, vortex finder geometry as well as wood feed rates and air flow rates. The characteristics and results of the optimised gasifier parameters was used to design the downstream gas cleaning systems such as the cyclone, condenser and filter.

4.12.1 System start up

To simplify the system gasifier and engine were designed and integrated with minimal control variables in mind. The prototype start up procedure involved the following initial functions. Extraction and air fan switched on; start up gas supply turned on for gasifier and engine; cooling water turned on; Monitoring equipment and thermocouples turned on.

4.12.3 Gasifier warm up procedure

The gasifier was first to be heated to initiate the reaction between the wood and transport gasification air. A tangential gas nozzle and spark ignitor positioned within the reactor was used to heat the internal reactor walls. The minimum wall temperatures at which the gasification reaction would initiate was determined by trial and error. The warm up procedure was optimised to obtain minimum time and start-up gas consumption. The lower reactor wall temperature required to initiate the gasification reaction was found to be above 500^{o}C however wall temperatures greater than 600^{o}C were used to ensure fast initiation. Warm up time of less than 15 minutes was achieved using 0.225m^3 of propane.

4.12.3 Gasification initiation

Once reactor was pre-heated (lower wall temperatures of 700 ^{o}C – 800^{o}C), the start-up gas and air were turned off. The wood feeder was set to required mass flow rate and turned on with sufficient transport air to entrain sawdust particles into inlet flow. Gasification initiates almost instantaneously, after which air is increased to ideal air / wood ratio. The system temperature is monitored and air flow levels adjusted to achieve exit gas temperatures of 900^{o}C. Reactor exit temperatures were found to be stable within ± 20^{o}C.

4.12.4 Engine start up and change over

Once reactor was warmed up and gas turned off, the gas supply was then diverted to the gas engine inlet manifold. The engine was started on the start-up gas and ran to warm it up while gasification process initiated and stabilised. After a few minutes the wood gas was diverted through the cooler/condenser and into the engine inlet manifold. The start-up gas was reduced to a pilot level of 1% - 2%. Wood gas / air mixtures were adjusted to correct mixture ratio. Once engine was operational at 1500 RPM electrical loading could be applied to the alternator. The use of higher intensity spark plugs are thought to remove the need for pilot gas, but were not used within the scope of this project.

The flow charts detailing the experimental procedure for informing design process for automated control of a biomass CHP system are included in the Appendix.

5 Results and discussion

Over 30 iterations of gasifier design alone were carried out in development of the biomass CHP system as presented in this report. A significant level of IPR was developed which remains commercially sensitive, therefore, this section only presents the experimental results of the final system. The hours of operational experience with the gasifier was >100 with engine operation on the wood gas 15 – 20 hours.

5.1 Biomass feedstock

The fuel for the biomass gasifier development tests was sawdust sourced as various sawmill residues and manufacturing wood wastes from South Wales. The properties of the LCV varied between 16.2MJ/kg and 17.8MJ/kg. The particle sizes varied between powder < 0.1mm and 5mm. However, the sawdust was sieved to < 2mm by passing the feedstock through a mesh fitted before the hopper. Less than 2% of the feedstock was oversize and thus rejected. The moisture content of the fuels tested ranged from oven-dried particles to fresh cut sawdust with moisture contents of up to 20%. However, the preferred levels for moisture were less than 10%, with higher thermal/reaction stability being achieved with dryer feedstock.

The fuel used for the experimental work reported in this report was kept constant. Properties of the sawdust are shown in Table 5.

Table 5 Fuel input properties

Property	**Value**
LCV	17.6MJ/kg
Density	165kg/m^3
Moisture content	>10%
Particle size distribution	
2mm – 1mm	4%
1mm – 0.5mm	35%
0.5mm – 0.25mm	33%
0.25mm – 0.1mm	18%
< 0.1mm	10%

5.2 Gasifier input rates

The air and wood inputs to the gasifier were calculated as described in Section 4, actual measurement of air flow in operational gasification conditions was not taken due to the wood particles in the flow. The air flow result in Table 6 was taken from fan input flow and therefore subject to pressure induced errors.

Table 6 Gasifier fuel/air inputs

Wood feed rate	20 kg/hr
Air feed rate	400lts/min
Air/fuel ratio (mass)	1.4:1

5.3 Temperatures

Temperatures were taken once system reached equilibrium and then time averaged over the test period, results shown in Table 7.

Table 7 Temperatures within system

Temperature (1) – ambient air	15°C
Temperature (2) Reactor	~800 °C
Temperature (3) Gasifier exit	900 $^{+-}$20 °C
Temperature (4) Cyclone exit	700 °C
Temperature (5) Condenser exit	30 °C
Temperature (6) Engine exhaust	(instrument error)

5.4 Wood gas composition

The composition of the wood gas was measured using a 'Testotherm gas analyser'. The results shown here were taken at an earlier stage of the project for a gasifier configuration slightly different to the final system that was used for the final engine operation tests, however, the gas composition (as shown in Table 8) is expected to be similar and therefore used for the analysis.

Table 8 Wood gas composition

Gas	% v/v
H_2	9%
O_2	1.2%
N_2	57%
CH_4	2%
CO	15%
CO_2	13%
Other C_xH_x	0.9%

5.5 Wood gas output from gasifier

Accurate measurement of wood gas output flow rate was difficult with the equipment available. Flow rate was derived by two methods:

Flow rate calculated from velocity of hot gas after cyclone using equation.

$Q = U A$

Where Q is the volumetric flowrate, U is the velocity and A the cross-sectional area.

Therefore, at wood gas outlet velocity of 7.5m/s the flow rate is calculated to be approximately 800lts/min. A rotameter in the wood gas flow after the condenser was used and recorded flow rate of 700lts/min, this flow was subject to losses over the cyclone and cooler/condenser system. Therefore within the uncertainty limits 750lts/min was assumed for total wood gas output flow.

5.6 Calorific value of wood gas

The calculation of the wood gas was carried out by referral to gas composition results Table 8 and properties in Table 3.

LCV of gas = 5.7MJ/m^3

5.7 Efficiency of gasification

Gasification efficiency is calculated by:

Efficiency = $Q \times LCV_{gas} / LCV_{wood} \times m$

Where Q is flow rate of wood gas and m is mass flow rate of wood

Gasification efficiency = 75%

This compares favourably with the efficiencies of other gasification systems, such as the down draught where values of less than 70% are achieved.

5.7.1 Energy balance

The 25% energy loss in the system is attributed to a small proportion of un-burnt char, heat loss from the reactor with the residual energy being used in the gasification reaction.

The break down is calculated and shown in Table 9.

Table 9 Energy loss in reaction

Energy content	%
Wood gas	75
Residual energy value in char	8
Heat losses and energy for reaction	17

5.8 Solid outputs from gasifier

The ash and char collection from the gasifier separation pockets was found to be 4.1% by weight. The configuration in this test saw that most particles were separated out in Pocket 1 with only a few larger particles collected in Pocket 2. A small amount a very fine particles were found in the cyclone. Results are shown in Table 10.

Table 10 Particle separation in gasifier and cyclone

Vessel	Percentage of biomass input	Size of particles
Pocket 1	3.7	10 μm – 0.5mm
Pocket 2	0.3	> 1 mm
Cyclone	0.1	< 10 μm

5.9 Ash percentage in solid particle collection

The particles collected in the collector pockets were weighed and then burnt out and re-weighed to measure the ash content, which was found to be 40% by weight, which as a result it was calculated that carbon burnout in the gasifier was 97.3%.

5.10 Liquid outputs

5.10.1 Condenser

The condensed liquid at 30^{o}C from the wood gas was measured to be 40g/kg (4%) of input fuel. This liquid was of transparent grey appearance and assumed largely water with traces of tar, however no analysis was conducted to determine exact concentrations of the condensate due to limited time and resource (this will be analysed in future work).

5.10.2 Engine oil

The period of operational experience of the CHP engine running on the wood gas was in the order of tens of hours and therefore no hard data on oil contamination is included in this report as test periods of up to a thousand hours would be necessary to give a quantitative & and qualitative result of the impact of contaminants contained in the gas on the engine.

5.11 Alkali content

Alkali measurements were not carried out in this project, however, experience in other entrained cyclonic gasifier projects found levels of Potassium to be in the range of 6 – 15 ppm (volumetric) and Sodium levels in the range of 1 – 3 ppm (volumetric) in the wood gas. These levels would be lower in the system used in this project as high particle separation, lower air to fuel rates and controlled reaction temperatures are involved. These key factors were deemed to be key features in reducing alkali content in the wood gas.

5.12 Tar content

The residual tar content within the gas was not measured after the gas cleaning system was installed, however earlier analysis undertaken on the gasifier during development showed tar levels of less than 4% in the untreated wood gas. As stated in Section 6.10.1 after running through a condenser a black water based liquid is thought to contain a large percentage of the tar formed in the gas.

5.13 Engine inputs

The engine wood gas and air consumption flow rates as shown in Table 11, were measured for the maximum electrical loading conditions.

Table 11 Engine wood gas / air consumption

Wood gas	350lts/min
Air	840lts/min
Engine air/wood gas ratio	2.4

5.14 Engine outputs (electrical)

The alternator was progressively loaded to 10kW for a length of time suitable for monitoring fuel input rates and engine operation. Under the time constraints of the project, effects of long term running of the engine was not investigated.

5.15 Engine outputs (heat)

The engine used to substitute the 45kWe Ford CHP engine was a Lister air-cooled engine and therefore did not have the heat recuperation system suitable for measurement of thermal efficiency. Thermal energy (*Q)* would be calculated from the temperature difference *(dT)* of heat transfer fluid using equation: $Q = m*Cp*dT$. Where *Cp* is the specific heat capacity and *m* the mass flowrate. A standard heat recovery system used in CHP engines would have provided 20kW of heat output.

5.16 Cooler/condenser outputs (heat)

For operation of a biomass gasifier and IC engine CHP system heat from the cooler/condenser system would also be factored into the heat retrieval circuit.

5.17 System electrical efficiency

The overall electrical and thermal efficiency calculated for the prototype system is not representative of the total achievable efficiency as even though the gasifier was turned down to accommodate the smaller engine used for the final demonstration, as previously described considerable volume (~ 55%) of the wood gas was combusted and expelled through the extraction system. Therefore estimated electrical and thermal efficiencies are based on the actual gas volume consumed by the engine at maximum load, rather than the total gas output generated. This is then factored by the gasification efficiency, which is based on the gas composition results, the variables for the calculation are shown in Table 12.

Table 12 Electrical efficiency data

Energy input (fraction of sawdust used to fuel engine)	44kW
Gasification efficiency	75%
Electrical loading applied	10kW
Calorific value of wood gas	5.7MJ/kg
Electrical efficiency (calculated)	22.7%
Wood gas to electrical efficiency	30.1%

The gasifier was turned down as far as possible, but still operated higher than the engines requirement, therefore the calculated figure of 22.7% for the electrical efficiency of the overall system is subject to the uncertainty under such experimental conditions.

5.18 Development results

The presented results were taken from the final testing programme as all prior data collected was taken as part of ongoing design and development. Reproduction of such experimental data within this report would not provide the reader with useful information without an indepth knowledge of the stage of development programme to which the data relates (which can not be provided practically with out breaching confidentiality).

5.19 Operational/development problems

The main problems encountered within the development of this swirling flow gasifier were the suspension of particles in the transport air. Even though cold flow tests were promising, the initial high density of un-reacted particles and the reduced viscosity of the hot transport gas meant that major problems of particle build up occurred in the bottom of the gasifier. Much work was focussed here in order to reduce the air flow rates relative to the wood feed rate to achieve ideal gasification air/fuel ratios. Inlet particle velocity, reactor geometry and novel particle deflectors were the main factors in assisting particle entrainment.

Particle collection within the reactor also required significant development work as the flow characteristics were changed to optimise the system.

Feeding the fine wood particles into the high velocity inlet air flow was found to present problems. Venturi feeders required high pressures which would have raised capital costs. The development of a novel feeder design meant a high pressure fan was suitable to deliver the wood particles in a high velocity air stream.

Avoiding high pressure drop across the system was also a development issue to be overcome, especially for the down stream gas cooling and cleaning equipment. Careful design was incorporated to ensure minimum frictional flow losses through the cyclone, cooler and oil bath.

6 Brief economic analysis

To conduct a brief economic analysis of the planned commercial biomass system the following section used data and findings from the prototype system and made assumptions where experience of running a commercial system was not available.

The system costed is a 50kWe system as tested in this project, however enhanced economics will be achieved by the planned larger systems of 250kWe.

The calculations rely on the feedstock being available at consistent particle sizes, therefore no provision for grinding is factored in.

6.1 Capital cost

The predicted capital costs of the 50kWe system are based on a system developed further considering manufacturing cost reduction, these are shown in Table 13.

Table 13 Capital cost for biomass system

Equipment	Cost (£)
Dryer	5,000
Wood feed system	5,000
Gasifier	10,000
Gas cooling and cleaning	5,000
CHP engine/alternator	30,000
Control system and electrical	5,000
Total	60,000

6.2 Fuel costs

The sawdust sourced for the project was manufacturing wood waste from local furniture manufactures. Their current position for disposal of their waste meant that the fuel was available for collection at no cost. A preliminary study into sawdust availability showed that approximately 20,000 tonnes per annum would be available in the South Wales area. If sawdust had to bought in, the cost of that sawdust would be £20/tonne.

The fuel consumption is calculated from the requirement of approximately 140 tonnes per annum.

6.3 Running costs

The system is designed to be fully automated and therefore only requires minimum operation and maintenance costs which can be calculated on a price per kWh of 1.5p.

6.4 Heat and electricity value

6.4.1 Electricity

Assuming 80% total operation per annum the 50kWe system would generate 350400kWh per annum.

The value of the electricity generated is calculated on the basis of deriving a value for the electricity up to 6p/kWh (if all the electricity can be used on site).

6.4.2 Heat

It has also been assumed that a value for heat would be 1p/kWh and the heat/electricity balance is 1.6, then 560,000 kWh thermal energy will be available (assuming all thermal energy is used).

6.5 Economic analysis

To evaluate the economics of this very small biomass CHP system, the following break down in Table 14 illustrates the main costs.

Assumptions are made that this equipment would be installed on a site where sawdust is a waste stream and that a small building is available for housing the system.

Table 14 Economics of 50kWe biomass system with installed cost of £60,000

Outgoing	Cost (£)
Fuel costs (up to £20/tonne)	0 to 3,000
Operation & Maintenance costs	5,000

Income	
Electricity value (5.5p/kWh)	19,000
Heat value (1p/kWh)	0 to 5,000
Annual revenue	**11,000, – 19,000**
Payback	**5.5 – 3.1 years**

The planned size of a small-scale commercial system would be greater than 50kWe, for example a 250kWe system would generate 1752000kWh electricity pa, producing electricity valued at £96,000 and heat valued at £26,000. By improving the capital cost of the system at this larger size to £1000/kWe, therefore total installed cost of £250,000. Using similar analysis as above the annual revenue could be £60,000 to £86,000, therefore improving the economics to payback in 2.9 to 4.2 years.

The comparison of the swirling flow gasifier CHP system with existing down draft system CHP technology provides savings of £280/kWe which is almost 22% cost reduction, and this is on top of the reduced operation and maintenance costs that are achieved with this system.

7 Conclusions

The conclusions drawn from the development of the small-scale biomass CHP system are made in the following points:

- A compact biomass gasifier based on entrained swirling flow gasification was developed and proven to provide an efficient method of conversion of sawdust into wood gas. The system benefited from reduction of 20 - 30 times in physical size when compared to a typical down-draught gasifier, this will reduce equipment costs.

- The gasifier proved to be very efficient, offering 75% energy conversion from wood to gas.

- The gasifier incorporates two stages of particle separation within the reactor, which collected a large part (3.9%) of the ash and char from the gas leaving only 0.1% of sub 10μm particles to be separated in a high efficiency cyclone. This also offers reduction in cost of particle separation equipment.

- Compared with air gasification systems, the gasifier developed in this project produced a good wood gas containing 5.7MJ/kg.

- The operational experiences of the prototype biomass CHP system found that due to the stable operational characteristics and the rapid response of the gasifier to the engine, automated control of the process could be simply applied using a PLC system.

- The spark ignition IC engine was run successfully on the wood gas with a very small trace (1% - 2%) of pilot gas. It is thought that this pilot could be entirely removed with further development work.

Therefore a significant reduction of capital equipment costs can be achieved over current biomass conversion technologies thus enhancing the economics of small-scale heat and power systems. The system has been successfully proven, but not suitable in its current form for commercial use. Commercialisation of the technology is possible once steps one and two from Section 8 have been completed.

The predicted system cost already compares favourably to the costs of competing down-draught gasification systems, however it is proposed that further design for cost reduction will be undertaken and focus on reducing engine costs.

8 Recommendations and further work

The following recommendations are proposed in the form of further projects, each covering specific aims of the development of biomass energy systems based on the swirling flow gasifier.

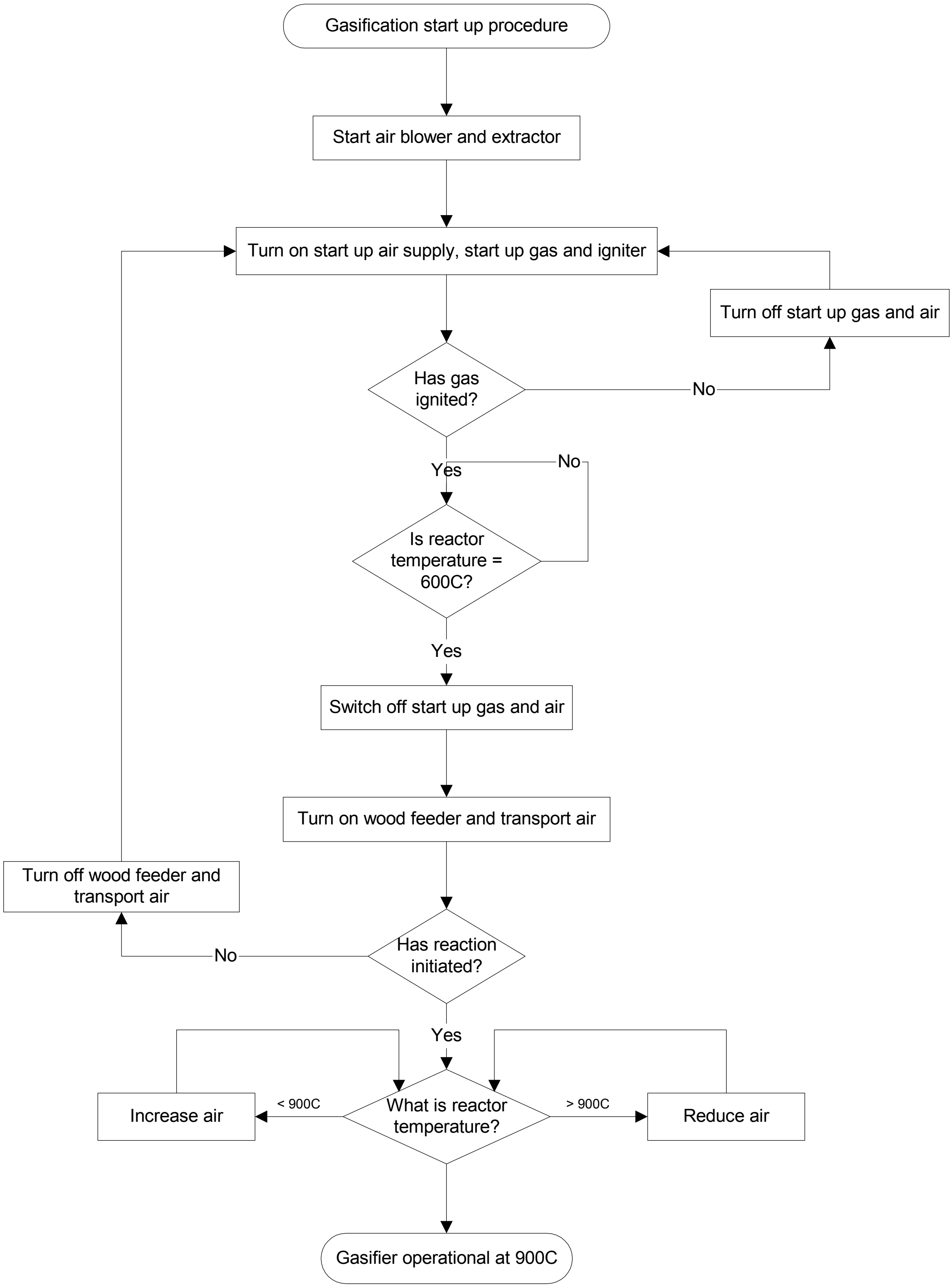
1. Connecting the gasifier back up to the 45kWe CHP engine, design and integrate automated feeding system, simple control and monitoring system and run for continuous operation trials. Objectives of optimisation of system efficiency, testing of contaminants to engine oil and fine tuning of system.

2. Develop pre-production unit incorporating design for low cost manufacture. Commissioning and commercial demonstration of the small-scale biomass CHP system.

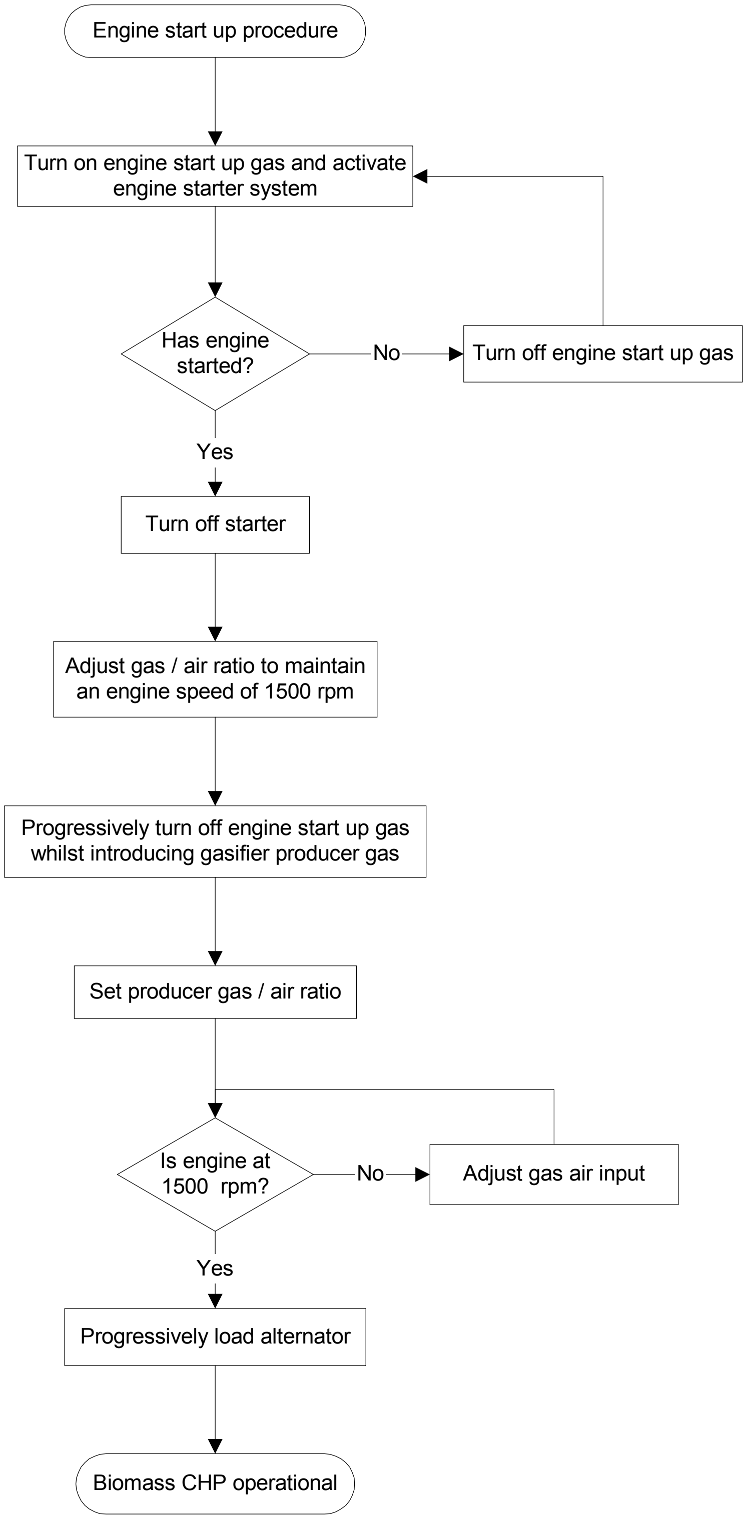
3. Pressurise the gasification process and secondary separation cyclone and fire clean wood gas through a secondary combustor and through a gas turbine for heat and power generation.

4. Gasification of other pulverised biomass feed stocks with full gas and by-product analysis. Fuels to be used include, chicken litter, dried food wastes and other segregated waste streams.

Appendix



Appendix Figure 1 Gasifier operation procedure



Appendix Figure 2 Engine operation procedure