Programme Area: Bioenergy

Project: Energy From Waste

Title: Appendix D: Power Generation

Abstract:

This deliverable forms part of Deliverable 2.2 in Work Package 2 and provides information on the gas engine and turbine rig scale testing.

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

ETI Energy from Waste FRP Project

Deliverable 2.2

Technology Assessment Report

Appendix C – Power Generation

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Introduction

Within advanced energy from waste systems, process technologies convert the waste material feedstock into a secondary fuel. To enable the energy in this fuel to be recovered for the generation of electrical power a further technology step is required. Maximising the efficiency of energy recovery from a material requires every step of the system to be as efficient as possible. Additionally, for systems to be commercially deployable, they must be of low operational cost, which implies operational robustness.

The most applicable final energy recovery for power generation technologies were identified in deliverable 2.1 of the ETI Energy from Waste project as being Internal Combustion Engines, Gas Turbines and Fuel Cells. Gas boilers with steam turbines were identified as a potentially suitable conversion technology but were not proposed for further evaluation due to the well characterised nature of this route as well as the relatively low achievable conversion efficiency compared to the above listed technologies. Fuel Cells as a technology family were also identified as being designed for operation on pure hydrogen. In this respect, the operation of these on gases produced from the gasification of wastes, provided that any contaminants and additional constituents were removed, was not deemed to provide a technical challenge in theory.

In relation to gas reciprocating engines and turbines, operation of biogas (as produced from Anaerobic Digestion processes) was not identified as requiring further investigation due to the similarity of this gas (when cleaned of contaminants such as H_2S) to (cleaned) landfill gas. However, the operation of engines and turbines on gases derived from gasification processes ("product gases") was identified as being a major unknown, preventing modelling of these technologies as well as their commercial development and deployment. These technologies were also identified as being highly applicable to advanced energy from waste systems due to their low cost, proven operational concept and global supply chain, as well as potential to recover both heat and electrical energy with a high efficiency. To examine the feasibility of operating these technologies on typical product gases, a programme of experimentation of testing a reciprocating gas engine on clean representative gases was proposed and accepted. This report presents the results from those experiments.

These tests were designed to indicate whether the gas properties in terms of energy density and flame speed allowed for the operation of an internal combustion machine, and what the limits of performance would be based on current design constraints. Tests were carried out using gases blended from individual compressed sources, and as such were free of the contaminants usually present in "real" product gases, which also enabled the tests to be completed succinctly without additional complications presented by these contaminants. As such, though, these tests present an indication of how these technologies could operate under ideal conditions, and it should be bourn in mind that their performance under real world conditions would be expected to be affected by contaminants and other inclusions present in the gas.

Test Programme

Gases produced from gasification and pyrolysis technologies are often known as "product gases", and comprise of a mixture of Hydrogen (H_2), Carbon Monoxide (CO) and Nitrogen (N), with the potential addition of Methane, Carbon Dioxide and other dilutants. It should be noted that a product this is distinct to a "syn-gas", which is technically formed of Hydrogen and Carbon Monoxide. However, the terms are used interchangeably in industry, along with similar terms such as "wood gas". In all cases, the mixture of highly combustible elements (such as hydrogen) and inert dilutants presents a potential challenge for the use in combustion engines. This challenge related both to the stable combustion of the gas itself, as well as to the products created by the combustion process and their impact on emissions aftertreatment technologies for compliance with existing legislation.

The engine tests using product gas were carried out for this work to enable the establishment of a basic engine model for incorporation into the system level model under development in the project.

The engine used for this testing was a single cylinder test engine based on the geometry of the Caterpillar 3500 series of engines, which are available in both diesel and gas configurations. The exact configuration used for the testing was the 3501C configuration, which is a gas fuel configuration with electronic ignition control. This specially designed single cylinder test engine is located at Caterpillar's Technical Centre in Mossville, Illinois, and is shown as installed in the test cell in Figure 1. The engine has a bore of

170 mm and a stroke of 190 mm, with a compression ration of 11.3 and was operated using the standard valve timing at speeds of 1200 and 1500 rpm. Ignition timing was set to match the 50% burn interval for natural gas, based on the higher flame speed of product gases.
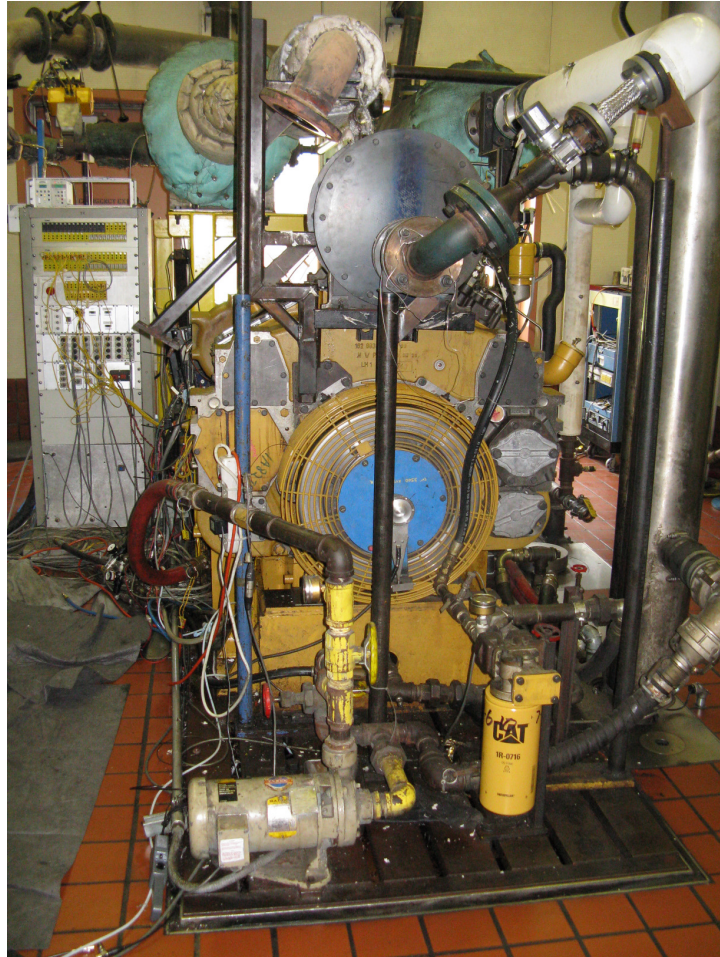
Figure 1 Photo of Single Cylinder Test Engine (Caterpillar G3501)

The operation of the single cylinder test engine was investigated using two gases with compositions representative of typical gasifier produced gases but with very different combustion properties. Due to timing constrains of the different experiments taking place in this Work Package, composition data was not yet available from the thermochemical rig tests carried out for this project at the time these gases were required to be ordered. To derive these gas compositions, a large number of customer enquiries made to Caterpillar and its dealers were examined. These enquiries were in terms of gas

compositions from the customers, based on their available feedstock and processing technology. Suitable compositions were then selected to represent the boundary conditions of the combustion of Natural Gas. The gas compositions tested are listed in Table 1 below:

Test	Gas composition (%)					LHV (MJ/kg)	LFS (cm/s)	Stoichiometric A/F (mass)
	H_2	CO	CO_2	CH_4	N_2			
1	39	37	17	0	7	10.7	99.0	2.55
2	18	18	14	2	48	4.2	37.9	1.16

Table 1 Gas Compositions of Gases Tested in Engine

Gas 1 is based on a high Hydrogen and Carbon Monoxide gas with no Methane, and has a correspondingly high flame speed and flame temperature, as illustrated in Figure 2 and Figure 3. As such this can be considered to be a "worst case" gas as regards engine operation. Gas 2 has lower proportions of Hydrogen and Carbon Monoxide, and includes a small amount of Methane. Gas 2 also contains a considerable amount of Nitrogen as a dilutant, resulting a lower specific heating value and lower flame speed. It should be noted that the values listed in Table 1 refer to the gas itself; when used as a fuel in the engine, the air fuel ratio must be appropriately determined with respect to the combustible components within the fuel. As such, the stoichiometric air fuel ration for Gas 2 is approximately ½ that of Gas 1.These gases were mixed by the gas supplier from pure component gases in the appropriate ratios, and hence were free from tars, particulates or other contaminants which are typically present in gasification gases and which could severely inhibit engine operation.
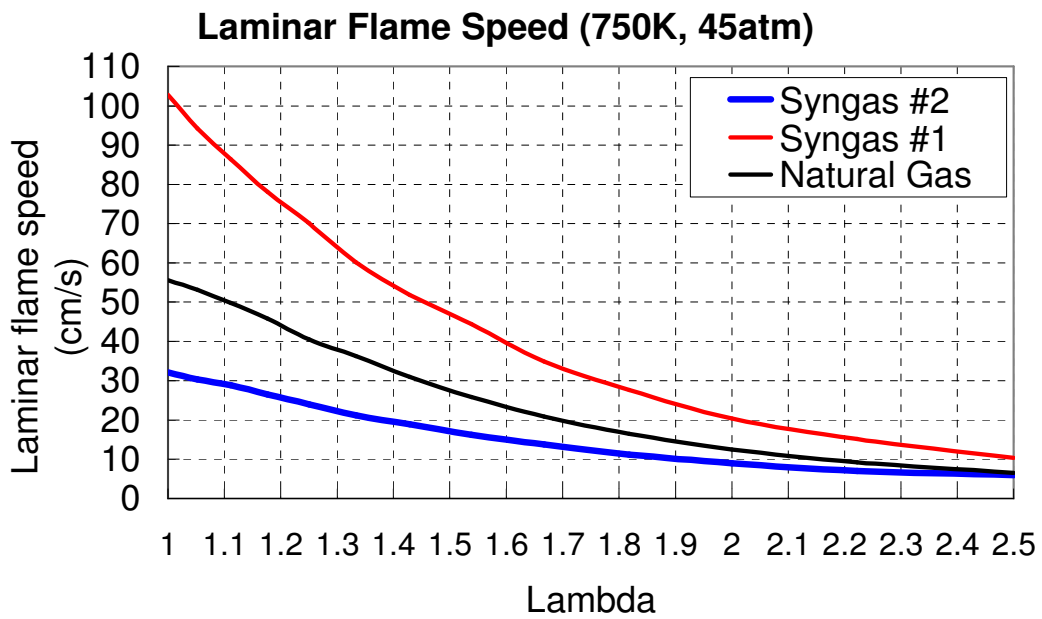
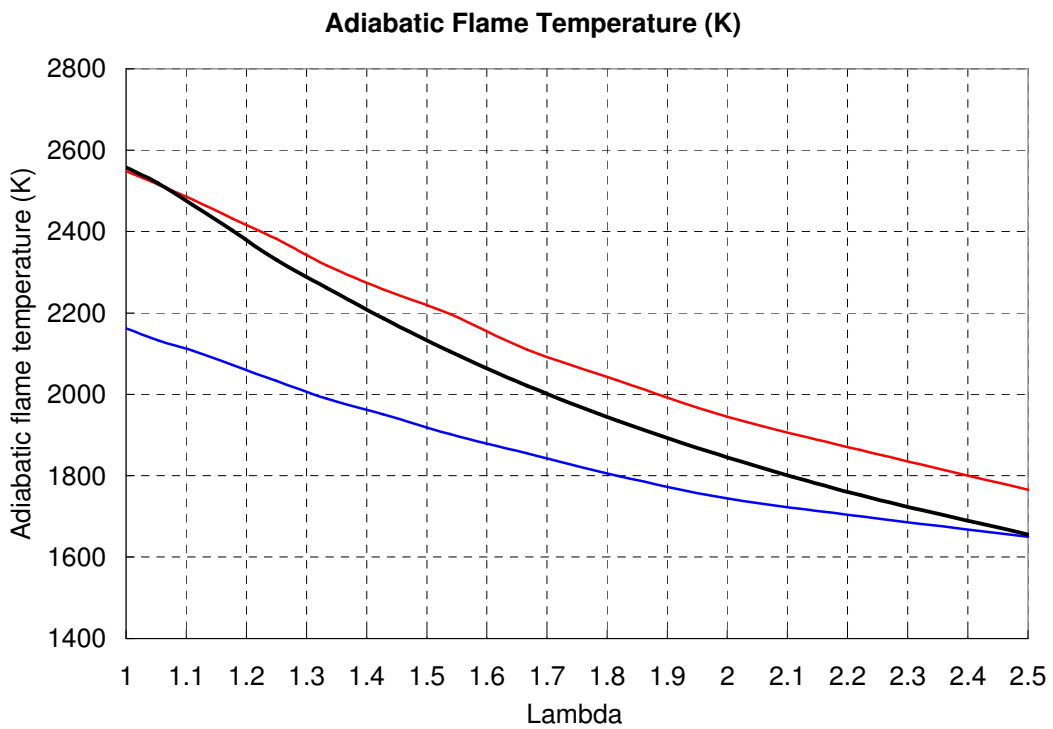Figure 2 Laminar Flame Speed for Test Gases

Figure 3 Adiabatic Flame Temperatures for Test Gases

Test Results

The air fuel ratio was varied from misfire (lean) to detonation (rich) for the set ignition timing. The air and fuel flow rates were recorded. At each condition, the break mean effective pressure (BMEP) was recoded in-cylinder, as well as the brake power at the crank shaft. The thermal efficiency as calculated from the engine out power divided by the fuel flow rate and energy content is presented in Figure 4 with respect to the BMEP for both gases (here called Syn 1 (Gas 1) and Syn 2 (Gas 2)).
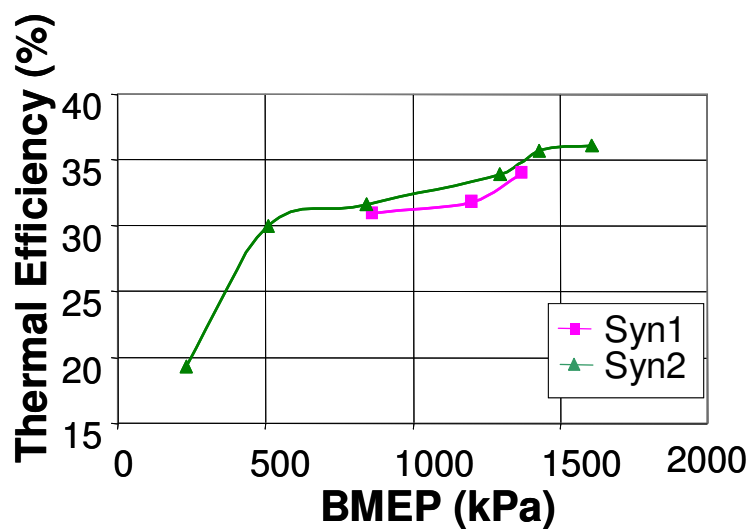

Figure 4 Graph of Engine Thermal Efficiency against Cylinder Pressure for different Gas Compositions

The maximum BMEP of SynGas1 was found to be limited by maximum allowable peak cylinder pressure. For both gases, the peak engine thermal efficiency was found to be around 35% at 13 bar BMEP. The test results also show both gases to have a good combustion stability over wide range of air fuel ratios, which is perhaps surprising given the high level of H_2 in the gases, and the potentially in-homogeneous (within the confines of the cylinder) mixture of combustible and inert gases. For both gases, high levels of CO were measured to be present in the exhaust, as would be expected for lean air fuel ratios. This suggests that further engine exhaust aftertreatment, such as the use of an oxidation catalyst would be required to meet current emissions legislation, as is currently the case for landfill and other gas engine applications. It should be also be bourn in mind that these tests were carried out under idealised conditions, using simulated gases

without the presence of any dust, tars or corrosive contaminants that would be expected to be present in gasification derived gases.

Operation of the engine using the synthetic gases resulted in visible degradation of certain engine components, even under the relatively short engine operating durations (4 to 8 hours). Due to the back-to-back testing of the gases, it is not possible to differentiate between the effects of the gases, but deposits at the top of the piston and rust on the piston and spark plug are shown in Figure 5, Figure 6 and Figure 7 respectively. Such effects have never been observed when operating on Natural Gas, with which Caterpillar has extensive experience. The source of the carbon is unknown, but may be due to the high levels of carbon released during the combustion of carbon monoxide. The presence of rust on the piston and spark plug suggest high levels of water vapour, most likely present from the combustion of hydrogen.

Figure 5 Carbon Deposits at Top of Piston

Figure 6 Rust on Piston Crown

Figure 7 Rust on Spark Plug

Gas Cleaning Requirements

The testing of the processing technologies for this project has shown the presence of a range of contaminant species in the gas. Failure to properly clean the raw producer gas prior to admission to an engine or turbine will lead to, amongst other things, ignition system failure, fuel system damage, piston ring/liner issues, oil contamination (and resulting bearing failure), high emissions of regulated emissions and damage to engine catalysts. All of these detriments would result in a shortened engine or turbine life, and hence ultimately in higher energy costs. Likewise, even trace levels of any of contaminants would result in poising of the active portions of any type of fuel cell, rapidly decreasing its performance and useful life, again resulting in higher energy costs. To enable robust and efficient system operation, the primary contaminates that need to be

considered from a power generation technology view are ash, particulates, tar, alkali metals, ammonia, sulphur and chlorine. The source and impact of each of these contaminants are listed and discussed below.

Ash

- Inorganic fraction of (largely organic) raw fuel
- Typically 0.5% to 10 % for biomass and waste materials
- Generates particulate matter in gas (see below)
- Depending on composition, may be classified as hazardous material - Disposal issue

Particulates

- From ash in feedstock and general "dust"
- Typical levels:
    - Fixed Bed 100 – 8000 mg/Nm^3
    - Fluidised Bed – up to 100,000 mg/Nm^3
- Engine tolerance level: 25 – 50 mg/Nm3 (maybe 10 mg/Nm^3)
    - <10 μm in diameter
- Can be removed with:
    - Cyclone
    - Wet scrubber
    - Ceramic filter
    - Electrostatic precipitator

Common system is series of cyclones (low cost, simplicity, up to 95% (to <5 μm) when used in series), small particles captured in ceramic filters. High filter temperatures can lead to sintering and cracking, whilst low temperatures do not remove the accumulated particulate mass. Particulate filter technology operating at low temperature has proved sufficient. Wet scrubbers offer some particulate removal, and are also effective for tar removal. Elector static precipitators also used for both, but are expensive. Generally, particulate removal can be achieved at reasonable cost

Tars

Covers wide range of hydrocarbvons and oxygenates, including polyaromatic hydrocarbons, aromatics, phenolics and olefins from incomplete breakdown of material

molecules which condense when the gas temperature falls below approximately 400 ℃, although the exact temperature of condensation depends on the molecules present, with most condensing between 120 ℃ to 250 ℃. Some molecules form aerosols which are not effectively removed by particulate filters.

- Typical values:
    - Downdraft up to 6,000 mg/Nm^3
    - Fluidised bed up to 30,000 mg/Nm^3
    - Updraft up to 150,000 mg/Nm^3
- Engine tolerance ~100 mg/Nm^3

The most common form of tar reduction is their physical removal from the gas stream. however, this reduces the energetic value of the gas as these carbon and hydrogen molecules are now no longer present in the gas. Physical removal of the tars may be achieved with a wet scrubber Oil or water), which acts to cool gas, thereby condensing the tars onto particulates. These tar loaded particulates may then be removed with an Electrostatic Precipitator. However, if the gas is to be combusted in a gas turbine, it is likely the gas would be required to be re-heated for efficient system operation. This use of wet scrubbers results in large volumes of contaminated waste liquids. Further effort and energy is then required to separate the tars from the scrubbing liquid, although the tars can be re-gasified.

Tars can also be handled in the gas stream by breaking the molecules into their constituent elements. This can be achieved by thermal or catalytic cracking. Thermal cracking breaks the molecules into CO and H_2. This requires a relatively high temperature – up to 1200 ℃, which is usually only achievable with the addition of an energy input (e.g. plasma), which imposes a high parasitic load on the system, resulting in low overall system efficiency and hence a high cost of energy. The use of a catalyst to promote tar cracking reduces the temperature and time over which molecules are cracked. Typical catalysts are Nickel or Dolomite. Despite the interest in the use of catalysis for tar cracking approximately 20 years ago, un-resolvable issues involving catalyst degradation combined with their very high costs have meant that this technology has not undergone much recent development (either academic or commercial).

Alkali Metals

Alkali metals (lithium (Li), sodium (Na), potassium (K), rubidium (Rb), caesium (Cs), and francium (Fr)) may be present in feedstock materials. This is particularly the case for potassium and calcium from biomass, where these elements may be absorbed by the plant from the soil. Even where the values in the actual material are low, contamination by soil etc. can drastically increase their levels. These elements tend to Vaporise during gasification and form aerosols when the gas temperature falls below 600 °C, forming sticky film upon contact with surface (gasifier, gas clean-up, engine), which adheres additional particulates and aerosols, leading to rapid build up of surface layers. In fluidised bed gasification systems, this can cause agglomeration of bed material. In an engine, this gums up fuel valves, turbomachinery and ignition systems (spark plug), contaminates the engine oil and damages any gas cleaning and exhaust aftertreatment catalysts. In addition, surface corrosion is likely to occur in and engine/turbine due to the removal of the protective oxidation layer present on most metals, particularly at high temperatures, i.e. turbomachinery and turbine blades. Alkali metals can be removed from the gas stream using chemical adsorption techniques, or from the raw feedstock by washing the raw material with acids. However, it is by far preferable to use feedstock materials with low alkali metal content if possible, although from the analysis of the by-products of the thermal tests conducted presented in Appendix E, it does not appear that any material, including (demolition wood) produces a stream which contains low levels of these metals.

Ammonia

Ammonia is commonly present in gasification gases due to conversion of feedstock embedded Nitrogen to ammonia in the gasification process, where levels of 1% – 2% of N_2 in the feedstock results in 100's of ppm NH_3 (ammonia) in the produced gas. Such levels in turn result in 100's of ppm of NOx in engine exhaust. However, additional thermal NOX levels from combustion are usually low due to the low temperature combustion of H2. The total NOx level is usually above levels where NOx is regulated (causes "smog" and acid rain), and requires exhaust aftertreatment to bring it to regulated levels, although these catalysts are also affected by other gas contaminants as discussed above.

Ammonia can be removed from the gas stream using water scrubbing, although this does contaminate the scrubbing water. Despite the importance of NOx, the fact that the majority of development of gasification based systems has occurred in pre-regulated

times or in non-regulated countries means that very little work has been done on NH3 removal to date.

Sulphur

Sulphur present in the gas is derived from that in the feedstock material. Although levels are typically low in biomass, they can be high in waste materials, especially rubbers and other vulcanised plastics. The sulphur forms sulphuric Acid when in contact with water vapour in gas, particularly if steam is used as gasification medium, resulting in exceptionally high wear in downstream equipment. In addition, sulphur in the gas leads to the formation of Sulphur Dioxide from combustion. Sulphur dioxide is a regulated pollutant, and also caused damage to engine aftertreatment catalysts, potentially resulting in higher levels of other regulated pollutants. Sulphur can be removed from the gas stream, although this requires special equipment which increases system capital costs, and hence the cost of energy generated.

Chlorine

Similar to the source and effect of sulphur, chlorine derived from the feedstock material leads to the formation of Hydrochloric Acid when in contact with water vapour in gas, particularly if steam is used as gasification medium. This also causes extensive equipment and exhaust aftertreatment catalyst damage, as well as degradation of engine oil, decreasing its lubricity. Chlorine can be removed from the gas using water scrubbing, although this produces its own hydrochloric acid solution, which can be difficult and expensive to dispose of. Alternatively, absorption filters may be used although these are expensive.

Gas temperature

Lastly, an often forgotten "contamination" of the gas is its temperature. Although not an inclusion within the gas, this is a gas property which can hinder or compliment the operation of downstream equipment, thereby affecting the overall cost of operation and of energy generated. The exit temperature at exit from a thermochemical reactor is typically between 500 and 800 °C, although may be as high as 1500 °C in the case of a plasma reactor. This compares to typical equipment temperature requirements as listed below:
- Ceramic filter: <600 °C

- Fabric filter: 100 – 200 °C (higher with exotic materials)
- Engine: <40 °C
- Gas Turbine: >20 °C, < 90 °C

To optimise the total system efficiency, the gas temperature should require as little manipulation as possible, as any heating or cooling of the gas is an energetic parasitic load on the overall system. However, certain techniques employed to enable the removal of certain contaminants will alter the gas temperature, such as plasma cleaning (increase) or waster scrubbing (cooling). Therefore the end use and application of the gas must be considered along with the design of gas clean-up system to ensure an optimum solution is arrived at.

Gas Contaminant Measurement Protocol

Although the presence of contaminants in the gas adversely affects the operation of energy from waste systems employing a gas as the final fuel, the measurement of these contaminants is not straightforward. For this reason a number of different techniques exist for the measurement of each contaminant species, and hence great care must be taken in comparing data from different sources as different techniques will impose their own nuisances on the values obtained. In particular, the measurement of tars and particulates is subject to the greatest variation as the precise system layout and process temperatures will determine their condensation and formation, and hence their measured concentration as well as physical size. A protocol has been developed for the measurement of tars and particulates from biomass producer gases under European Union Funding (Good *et al.* [2004]). However, this protocol was designed without any input from possible users of such a gas (i.e. power generation equipment manufacturers), and so it is unknown whether the proposed technique is fit for purpose. The relative immaturity of the processing technologies under investigation in this project determines that a further investigation would need to be carried out to identify the appropriate tar and particulate parameters to measure, and their respective acceptable limits, prior to standardising a protocol for their measurement.

Conclusions

The tests of operating a reciprocating internal combustion spark ignition engine conducted for the ETI Energy from Waste project show that engine operation on gases

comprised of varying proportions of hydrogen (H_2) and carbon monoxide (CO) with adiabatic flame temperatures bounding that of methane ("Natural Gas", CH_4) is feasible. Using an engine configuration (compression ratio) designed for natural gas applications in conjunction with an optimised spark timing for the gas flame speed appears to indicate a thermal efficiency of 35% is achievable; it was beyond the scope of this work to examine whether the compression ratio could be optimised further, although this is likely to be highly fuel composition dependant, and hence difficult to define for "product gas" as a whole (due to wide range of compositions and properties this encompasses). The pictures and analysis of engine components post testing do show quite high levels of deposit formation, which appear to indicate increased service requirements when operating on these gases, although an accurate assessment of this impact would require longer term durability testing, which was beyond the scope of the present work. Similarly, the presence of tars, particulates, trace metals and other chemical contaminants (*e.g.* chlorine, sulphur etc.), as commonly found in product gases derived from waste material feedstocks, would be expected to have a highly detrimental effect on engine performance and longevity. However, these test results have achieved the project ambitions by proving the ability of using product-type gases in internal combustion machines, and deriving sufficient experimental data to derive a simple engine model liking the input gas composition to the power generated, as developed in Work Package 3 of this project.

References

Good J., Ventress L., Knoef H., Zielke U., Lyck Hansen P., van de Kamp W., de Wild P., Coda B., Paasen S., Kiel J., Sjostrom K., Liliedahl T., Unger Ch., Neeft J., Suomalainen M., Simell P. "Sampling and Analysis of Tar and Particles in Biomass Producer Gases – Technical Report", CEN BT/TF 143, 2004.