dti

BIOMASS FUELLED INDIRECT FIRED MICRO TURBINE

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Contractor

Talbott's Heating Ltd

Prepared by

David Pritchard (Talbott's Heating Ltd)

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Executive Summary

Project Aims

The aim of this project was to further develop micro turbine indirect firing and to develop this into a biomass generator, building on the success of the previous project. The system was redesigned and rebuilt using the experience gained and the recommendations reported in our last project. The efficiency, maintenance and safety of the system was improved through this development project.

Specific aims were:

- To achieve 4000hrs run time
- To establish a start procedure
- To develop safe and predictable operation without the need for supervision
- To prove heat exchanger concept
- To achieve full recuperated operation
- To achieve high temperature combustion with low emissions
- To establish costs and technical basis for future development
- To provide a demonstration of working biomass renewable power generation

Introduction

Talbott's Heating, working with Bowman Power, have developed, with the support of the DTI and ETSU, a biomass indirect fired air turbine system. The system was based on the Bowman TG50 50kWe turbine and a C3(S) combustor with a high temperature heat exchanger. The system is fired on biomass to provide electricity in a very efficient and simple manner. The "Biomass Combustion Gas turbine CHP" project has provided the proof of principle.

Biomass combustion represents a carbon dioxide neutral, renewable energy source and produces less carbon monoxide and particulate matter than an average gas boiler without sulphur emissions associated with fossil fuels.

This project aims to build on the success of the previous project by further developing and improving the system.

Converting biomass heat energy into electrical energy is currently limited. The traditional method involves producing steam by passing the hot biomass combustion gases through a waste heat steam boiler. This steam is then used to drive a steam engine or turbine generator. Steam based systems provide low fuel to electrical output efficiencies due to the dumping of heat in the condensation phase, as a result fuel feed rates are high and the electric outputs are low.

Small-scale steam based generation using biomass combustion is very expensive due to the steam raising and dissipation equipment needed, this leads to unacceptable payback periods. The economics of steam are hard to justify under 1MW due to low efficiencies and high capital costs. Steam is easier to justify when there is a use for the excess heat (CHP), but this relies on a constant demand for heat when the system is generating.

There is a large demand for a simple, highly efficient biomass generator under 1MW. Energy crops schemes being pushed currently require an efficient energy end use. The more efficient the biomass to electrical energy system is, the easier it will be to justify and promote energy crops. The smaller size system provides benefits in that fuel transportation costs can be reduced. An added benefit is that power can be provided where it is needed, reducing the strain, cost and power losses in cabling to remote locations.

Methods

A short report was commissioned to outline the specification of commercially available high temperature heat exchanger materials and to determine their suitability for indirect firing. This report confirmed our material selection and also provided material alternatives.

A new larger biomass combustor was manufactured at Talbott's factory in Stafford. The high temperature heat exchanger was extended with a new outer case designed, manufactured and fitted to the biomass combustor. A series of tests were conducted to evaluate the thermal performance characteristics of the biomass combustor and heat exchanger using the existing turbine generator from the previous project.

The PC based mathematical model of the system was adapted to take into account the physical characteristics of the system.

Bowman Power and Talbott’s worked together to re-commission the TG50 turbine to incorporate our new biomass combustion system. Modifications were made to the pipe work to reduce pressure losses along with extensive starting control software changes. Startup and shutdown procedures were developed and tested with over 100 successful starts.

Full recuperation of waste heat from the turbine exhaust is possible via modified ductwork and it is returned into the combustion air stream whilst maintaining combustion control; this provides a reduction in fuel consumption and improved emissions. Extensive modifications to combustor internals were made to cope with the high volume flow rates and temperatures without causing combustion problems.

The biomass generation system was tested for over 4000hrs and data captured in real time via PC based ModBus and other data logging packages. Generated power from the Biomass Combustion Turbine during the testing ranged between 20-30kW.

Although the system is still developing, and could benefit from an increase in both combustor and heat exchanger size, capital equipment costs for this 30kW_e prototype are around £2,500 per kW_e. Comparing this with our current steam based 50kW_e CHP system with an electrical efficiency of 8% and cost of £6,455 per kW_e, this represents a great leap forward at this size.

Commercial prospects for this technology are good with over 3,500 existing world-wide installations of our heat only systems. It is predicted that a large number of our previous customers will be interested in producing electricity from their existing waste fuel supplies. The 30kW_e unit could provide an offset to a normal base load of 250kW_e average in woodworking factories. With electricity being purchased at 5p/kW this would save £1.50 per hour, operating this unit for 8000hrs per year will save £12,000, ROC's(Renewable Obligations Certificates) will add another 3p/kW (although sold on the open market may yield 5p/kW), this will add a further £7,200. Therefore the payback period can be calculated to 4years. Heat output will make the system more attractive as well, by cutting gas or oil costs. Larger units with higher efficiencies and lower costs per kW will, of course, provide much faster pay back, a 250kW_e system is expected to have a payback period of just 2 ½ years.

Results

The starting procedure has been developed and is now well proven, with over 100 successful starts. The system has run for over 4000hrs, producing between 20-30kW in a very stable and reliable manner.

Heat exchanger performance has been benchmarked and durability has been proven. Materials for the heat exchanger have been studied and results obtained from actual running. A sample of heat exchanger tubing that was subjected to combustion temperatures ranging between 900-1150°C was submitted for testing after 4000hrs operation in order to evaluate the depth of oxidation into the underlying steel. A polished section was prepared perpendicularly through the sample and examined using optical light microscopy. The normal oxidation thickness of the piece is in the range of 5μm to 20μm thick and has formed as a continuous dense oxide layer. Occasional masses of up to 130μm thick are formed at grain boundaries within the steel surface.

All of the waste gases from the turbine are reused in the combustion chamber, giving 100% recuperation. System performance has been evaluated and benchmarked for further development.

Measured performance:

Combustion temperature testing range	900-1150°C
Turbine entry temperature testing range	700-850°C
Net electrical output testing range	18-35kW
Heat exchanger efficiency	71%
Exhaust gas temperature	300-330°C (for CHP)
Compressor isentropic efficiency	62%
Turbine isentropic efficiency	80%
Overall efficiency	15%

Measured emissions:

CO	0.001 to 0.01 vol %
CO_2	7.4 to 7.5 vol %
NO_x	2-10 ppm

Particulate emission 50 mg/m^3

Commercial and marketing research indicates a 100kW_e size would be the minimum size to be currently justifiable. The initial cost of a 100kW_e biomass generator would be around £250,000. With flow line production the price is expected to drop to around £200,000 for each unit. Producing 100kW_e in one year it will produce 800,000kWh of electricity. The electricity can be sold for 2p/kWh, in one year this will total £16,000. For each kWh, 5p can be received for the electricity producers ROCs; this will amount to £40,000/yr. Therefore the overall amount received for the electrical output will be around £56,000/yr.

Significant levels of carbon emission savings can be made through the use of this unit. Carbon emission savings made through the use of a Biomass Generator with an electrical output of around 100kW and a thermal output of around 150kW compared to traditional fossil fuel fired systems are calculated below.
Average CO_2 emissions from UK fossil fuel generators, including transmission losses are estimated at 183g/kWh, therefore:
100kW x 8000hrs x 183g = 146.4t/yr
Average emissions from UK fossil fuel boilers are estimated at 98g/kWh, therefore:
150kW x 8000hrs x 98g = 117.6t/yr
Hence, the total CO_2 emission reduction per year for each unit will be 264 tonnes.

Conclusions

The main achievements of these projects are:

- Start procedure established and well proven with over 100 successful starts
- 4680 hours turbine operation so far
- Safe and predictable operation without supervision
- Heat exchanger concept proven
- Fully recuperated operation achieved
- High temperature combustion achieved with ultra low emissions
- The Biomass Generator has demonstrated that it is possible to produce 20-30kW of renewable electricity in a stable, reliable manner
- Cost and technical basis for future development established
- Demonstration of working biomass renewable power generation

The concept is now well proven the next logical step is to improve the system and build on our success.

Recommendations

- To manufacture a new 100kW_e system
- To improve the overall cycle efficiency
- To re-design the biomass combustor to incorporate the higher air return temperatures and volume flow rates, other improvements could be incorporated inline with our experience of this system
- To utilise waste heat from the system in heating and cooling applications; thus making an efficient biomass fired Co-gen and Tri-gen system

Contents

1. Introduction

1.1 Background

Talbott's Heating, working with Bowman Power, have developed with the support of the DTI and ETSU a biomass indirect fired air turbine system. The system was based on the Bowman TG50 50kW$_e$ turbine and a C3(S) combustor with a high temperature heat exchanger. The system is fired on biomass to provide electricity in a very efficient and simple manner. The "Biomass Combustion Gas Turbine CHP" project has provided the proof of principle; see report "ETSU B/U1/00679/00/REP" for full details. The report details the successful demonstration of this system.

After writing the above published report the system was run again to maintain the turbine at generating speed. The turbine successfully maintained speed for 30mins whilst demonstrating the over-speed controls operated correctly. Components were under sized; however for the purposes of proving the principle the tests went ahead and were successful. Combustion temperatures however needed to be raised above safe working material limits, this was acceptable in the very short term but damage was done to the combustion system and it could not be run like this long term.

After completing these tests it was noted and detailed in the project report that areas of the Biomass combustor and heat exchanger could be improved. These measures will boost the system efficiency and life.

It was recommended to run a new system for a period of 4000hrs to provide data on the long-term effects on materials at the high temperatures. Maintenance and reliability issues were to be studied on this new system. The study should carefully monitor the condition of the system and seek to improve the overall cycle efficiency.

The 50kW$_e$ gas turbine, when adapted to run on biomass, provides in the region of 26-34kW of electric power. The only heat losses are from combustor/heat exchanger walls and the exhaust, the pipes and walls are to be well insulated to minimise these. Exhaust gas temperature can be high; this was reduced to improve electrical efficiency. Exhaust gases provide a good source of high grade waste heat that can be easily converted into hot water for heating.

1.2 Project Aims

The aim of this project was to further develop the indirect firing of micro turbines and develop this into a biomass generator. To redesign and rebuild the system using the experience gained and the recommendations reported in our last project.

Specific Aims:

- To achieve 4000hrs run time
- To establish a start procedure
- To develop safe & predictable operation without the need for supervision
- To prove heat exchanger concept
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2. Re-evaluation & Design

The results and knowledge gained in the previous tests were collated and used in the re-evaluation of the system. It was decided that the combustor was to be completely rebuilt from scratch with new controls. The heat exchanger would be extended, increasing its heat transfer capability and a new casing fitted to better guide the flow of heat and minimise losses. The existing turbine would be reused with software modifications. Details of these changes are described in the following sections.

2.1 Description of Generation process

Our generation system can be described as Biomass fuelled indirect firing of a gas turbine generator set. The system consists of a high temperature biomass combustor with integral recuperation, a matching high temperature heat exchanger, and a biomass turbine generator set. The system induces ambient air and compresses it. The pressurised air is then heated by the biomass combustion via the heat exchanger. The heated and pressurised air is then expanded in the power turbine, giving mechanical energy, which is then converted into electricity via an alternator generator. Turbine exhaust gases are recuperated into the combustor; therefore the system only has one exhaust which can be fitted with a waste heat boiler for CHP. The system can be operated on a wide range of biomass and solid fuels which can include some waste streams. The electrical output can be connected at very low cost to the grid via a standard 415/3/50Hz connection.

2.2 Combustor Design

The previous design experienced difficulties in handling the high volumes of returning high temperature air. These volumes and temperatures were measured during the previous trials, therefore the new combustor's air pathways were designed to suit these parameters and guide the air for the most effective combustion.

The Biomass generation system has significantly higher temperatures of combustion due to the process. Therefore high-grade insulation and ceramics were specified with increased wall thickness and the elimination of thermal shortcuts. New methods of insulation were developed for this project; this technology has now been adopted by Talbott's for their hot water boiler models which now benefit from increased efficiency.

The previous testing demonstrated a failure mode where the combustion chamber could become pressurised; the previous combustor was not capable of handling this situation safely. This area was addressed by eliminating atmospheric vents that are commonly used in negative pressure designs. An automatic pressure relief was incorporated, using the system's differential pressure. The control system was re-evaluated and now regulates the combustion pressure independently.

The fuel feed system was updated with increased safety features and controls. Solid fuel combustion systems have, as part of their nature, a higher delay in control terms. This is due to time taken to feed fuel into the system and for the reaction to occur and produce heat; this delay causes large oscillations in the temperature. Working with a controls company, a control philosophy was developed to minimize this and obtain the best possible control.

2.3 Heat Exchanger

Previous testing measured a higher temperature difference, indicating lower thermal efficiency. Therefore an increase in heat transfer area was required for the given geometry. The existing heat exchanger was still in good condition so it was decided to reuse its sections and add a new section in a higher temperature material. Materials expertise in this area was sought from a Stoke-on-Trent firm, who have a history of consultancy to kiln factories and experience in high temperature refractories and metals. Talbott's and Bowman also carried out an independent literature review in their respective areas.

2.3.1 Heat Exchanger Materials

An initial review of heat exchanger materials highlighted a stainless steel capable of operating at 1050°C, although operating parameters and characteristics are not well documented over 700°C.

2.3.2 High Temperature Oxidation

Metals combine with oxygen to form oxides. Stainless steels resist oxidation through selective oxidation with chromium, this forms a stable and slow growing oxide which forms a barrier and stops or slows other oxide formation and is know as protective scale formation. A method of measuring scaling is to measure the weight gained in the form of oxygen added into the scale. Nickel content often improves the metals stability at high temperature.

A regular problem with oxidation of stainless steels is when the scale detaches, causing a fast weight loss. Some of the causes are mechanical damage and abrasion, thermal cycling and an excessive oxide thickness. If this scale falls off then a new layer will be formed. In time the scale could take with it enough chrome for the base metal to lose its high temperature resistance, leading to rapid loss of material and failure.

At very high temperatures the chrome is evaporated and the metal underneath is consumed, causing excessive thinning and eventual failure.

2.3.3 Independent Search

The methodology employed for the search involved use of internet search engines (including specialist materials based web sites available to the consultants) use of library facilities, investigation of relevant, previously published scientific papers, contact with experts in the field and internal contact with the consultants. The aim of the search was to identify a replacement material for tubing which was used in a previous prototype design. The target material is to have the following technical and commercial properties;

- A high continuous operating temperature with minimal thermal cycling

- A low corrosion rate under biomass combustion conditions with an operating air temperature at around 1050°C giving an expected operating lifetime of several years

- Material available in quantities, lengths and format applicable to the project (e.g. wall thickness, seamless or welded tubing, available in multiple metre lengths)

- Commercially available with a relatively short lead time from ordering to delivery

- Acceptable price per metre. A higher temperature specified/higher corrosion resistance material will understandably be more expensive than the current material. However the increase in materials costs compared to the prototype assembly needs to be reasonable relative to the project budget and in the longer term needs to reflect an affordable price for potential customers of this technology

The long term functioning of the heat exchanger developed for this study will be determined by factors such as;
- Temperature history (peak and dwell temperatures, thermal cycling)
- Composition of the combustion gases in contact with the external surfaces
- Mechanical and design factors such as thermal expansion, vibration and pressures generated inside the exchanger

Temperature and corrosion resistance of candidate materials for this application therefore need to be assessed using the relevant data gathered from the previous pilot scale trial of the system (described above in the introduction). The temperature of the internal working surface of the heat exchanger tube array can be controlled according to the rate of biomass input and excess air input into the biomass combustion chamber. As indicated above the external temperature of the heat exchanger will be increased from around 900°C delivered in the prototype unit to around 1050°C for the current design. The composition of combustion gases likely to be present at the external heat exchanger surface can be assessed using data collected during the prototype study. The effect of internal gas pressure of the heat exchanger array under these conditions will be assessed using computer aided modelling (the subject of the accompanying report).

The probable gas composition range which is expected to be present at the external surface of the heat exchanger (biomass combustion side), as based on measurements taken during prototype trials and analysis of the biomass fuel, will be as follows:

O_2 levels in the range of 10% to 14% by volume
50 ppm CO (@ 15% O_2)
Estimate up to 10% by volume of water vapour
48 ppm NO_X (oxides of nitrogen @ 15% O_2)
Estimate of 10 to 15 ppm of SO_X (oxides of sulphur)
Particulate emission 50 mg/m^3
VOC emission 1.3mg/m^3 (carbon)
Balance as nitrogen

The above figures for the biomass-fed, gaseous environment to be expected at the heat exchanger surface indicates fairly strong oxidising conditions will be present, but relatively low levels of oxides of sulphur and nitrogen are to be expected. The high level of oxygen in the gas stream indicates that candidate materials which have higher oxidation resistance should be favoured. The relatively low levels of sulphur present in the gas stream indicate that sulphur may speed the oxidation process rather than initiate sulphidation by penetration at the grain boundaries. Some particulate content is measurable in the gas stream. It is reasonable that at least a proportion of the particulate material is derived from the ash content of the biomass fuel in addition to a proportion of char particulate material (combustion product of lignin). The particulate content will therefore constitute a mode of transport of inorganic materials to the heat exchanger surface. The inorganic constituents of the particulate matter may therefore include small amounts of calcium, potassium, sodium, magnesium, iron and phosphorus oxides as well as silica and some sulphate content. To conclude it is important to note that wood and wood products generally contain small but significant amounts of halogens and alkali metals plus minor amounts of other elements. These elements potentially constitute aggressive species with respect to corrosion attack of many types of metal alloy operating at high temperatures in biomass fuelled applications.

The initial Phase 1 materials selection meeting was used to explore the possibilities for which classes of heat exchanger material should be considered in the search. The first approach to take is to list all commercially available classes of high temperature metals, or other materials, which could technically be employed to fabricate the heat exchanger. The following classes of metals were included in the materials selection exercise:

- High temperature stainless steels
- Ceramic spray coated stainless steels or other metal/alloy substrates
- Wrought alloys
- Oxide dispersion strengthened alloys
- Intermetallic compounds
- Refractory metals
- Single crystal metals

2.4 Turbine Generator

The existing TG50 micro gas-turbine from the previous project was to be reused and improved where possible. The modifications made to the turbine are detailed below.

Firstly the internal compressor and turbine pipe work was modified to reduce pressure loss and reoriented to suit the new combustor. This involved reducing the number of bends and providing better flow paths. An additional expansion joint was added to remove thermal stresses and aero derivative connections were replaced with commercial flanges suitable for current pressures and temperatures. Pipe work was also inspected and cleaned internally to prevent debris from entering turbine internals.

The system had previously been fitted with a smaller trickle charger to top up the two 24v batteries between starts. Starting this system using gas would normally only require motoring of the turbine for less then 2min at most. The biomass starting procedure required motoring for up to 30min; therefore a 24vDC power supply was added to the generator to allow for this extended starting cycle.

Generator case temperatures were higher than with gas operation, this was due to additional hot pipe surface area. Additional insulation was added to maintain a case temperature that was acceptable for electronic equipment.

A material study investigated turbine components to check suitability for use under biomass firing temperatures. It was found the components of the turbine combustion chamber, particularly the housing, required cooling air not present in the biomass firing system. This resulted in a limiting temperature of 800°C been advised by Bowman Power, until this component was replaced with a higher grade material or had a protective coating applied.

3. Initial Testing

Once the manufacturing was completed, a series of tests were conducted to establish the systems characteristics. During these tests problem areas could be discovered and resolved. Other areas are improved.

3.1 Combustion system

The combustion grate system was modified twice during these trials to give better performance. The combustion air duct work was modified to improve the start up condition with controls to ensure that it did not interfere with the normal running cycle. Several inducted draft fans were tested to find the optimum unit and running speed.

3.2 Turbine

During commissioning of the turbine air leaks were discovered and sealed on several joints. After initial commissioning works starting problems were discovered. Even though we had increased the thermal output of the heat exchanger the engine's response was similar to the previous project, i.e. large thermal forces were being used to drive the turbine but very little acceleration force was being produced. After ruling out all other possibilities, the engine was removed and stripped down for inspection. On inspection it was discovered that the engine was faulty.

A new engine was fitted and commissioned, from the start this engine's performance was completely different to the unit we had been testing. Acceleration was much faster with much lower temperatures, the warm system now accelerated to generating speed in less than 2mins and the difference could be clearly heard. Since then no further engine problems were experienced and over 4000hrs have been run.

3.3 Controls

With the system operating correctly, a start up routine was developed to control the start of the system automatically. The system comprises of a Combustion control panel using a dual loop PID controller with variable speed drives. The combustion control panel is connected to the turbine computer controller by MODBUS protocol and relay connections. Data logging is incorporated in this system via a PC and records all sensor output data values, such as temperatures, pressures and speeds every second.

3.4 Starting procedure

During the commission phase a starting procedure was developed and control logic programmed to automate the process. The starting and operation was designed to be as easy to operate as possible with the minimum of technical knowledge and user intervention. The following will briefly describe the starting procedure from an operator's perspective.

A small list of pre-start checks is performed to ensure the system is in good working order.
Fuel is pre-fed into the combustion chamber ready for ignition, the operator at this time will be able to check feed system is operating correctly and the fuel is acceptable in terms of moisture content and consistency. The combustor is then lit manually and the doors are closed. The control switch is turned to the on position; this starts the combustion fan and feed systems. The combustion system and heat exchanger are allowed to slowly heat up over 1-2hrs; establishing the fire and minimising the thermal stress on the ceramic and steel components. Once the system has reached 750-800°C the operator can press the generator start button to begin the turbine start sequence. Under normal operation the generator does not need further input from the operator.

The turbine controls automatically check its sensor train for faults before allowing the turbine to continue. If the system has not been used for a while, the lubrication oil may need to be warmed to ensure sufficient lubrication to the bearings and prevent wear or damage. This lubrication oil heating occurs automatically and once up to temperature allows the turbine to begin motoring electrically.

The turbine operates at a low speed to warm the engine and oil system for 10-30min. During this stage heat from combustion begins to be transferred to the turbine then back to the combustion.

Temperature increases towards the lift off turbine inlet temperature, when the turbine reaches the lift off temperature the turbine accelerates briskly to generating speed. Generating speed is 100,000 rpm on biomass power; the speed is controlled while the system stabilizes. After a few minutes the generator synchronizes with the grid and the system begins to generate. See Figure 3.1 for a typical test trace.

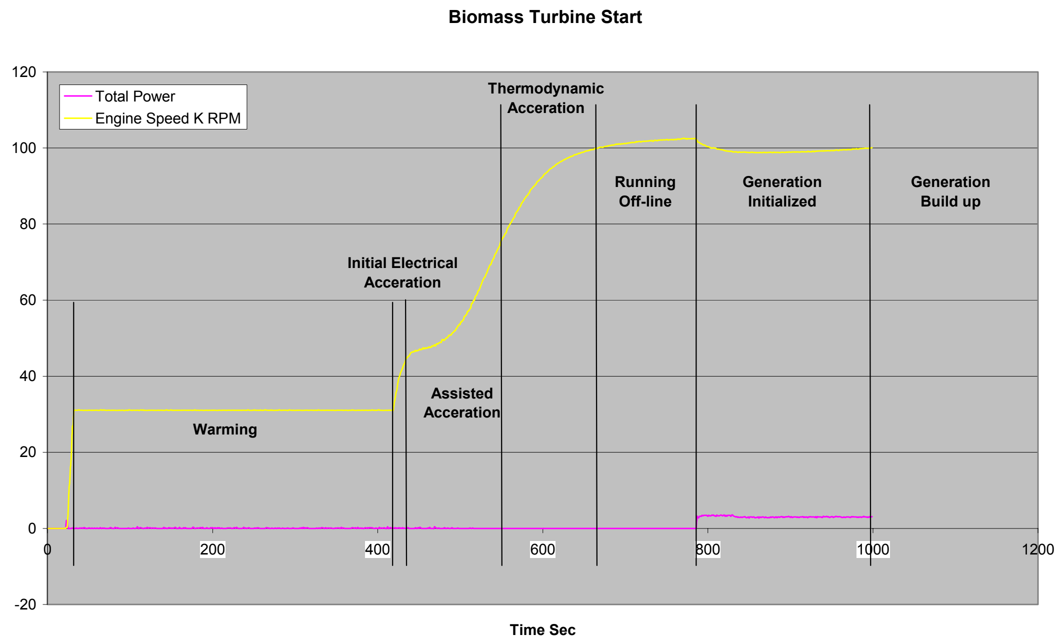


Fig 3.1 Typical starting speed response

The operator may then increase the turbine inlet temperature to increase the generated power to the level required.

3.5 Safety devices

- Inter-linked E-Stops mounted by exits & control panels
- Pressure relief valves
- Burn back in screw – Screw shunt & water dosing system, air locked rotary valve
- First aid kits & fire extinguishers

3.6 Controlled Shutdown Procedure

The shutdown procedure is fully automatic and simple.
The operator turns the shutdown switch to the "on" position. This stops the flow of fuel from entering the combustion chamber. The system cools slowly over 45-60min whilst still generating on a reducing scale. When the turbine can no longer generate the turbine is off loaded and slows to a stop. This method uses and removes the residual heat from the system. Cooling the system in this manner reduces thermal stress and prolongs material life. Due to the high insulation, heat will remain in the combustor for a long time. The unit should be left a minimum of 12hrs before de-ashing. The ID fan will automatically switch off after cooling the combustor to a preset level. See Figure 3.2 for a typical test trace.

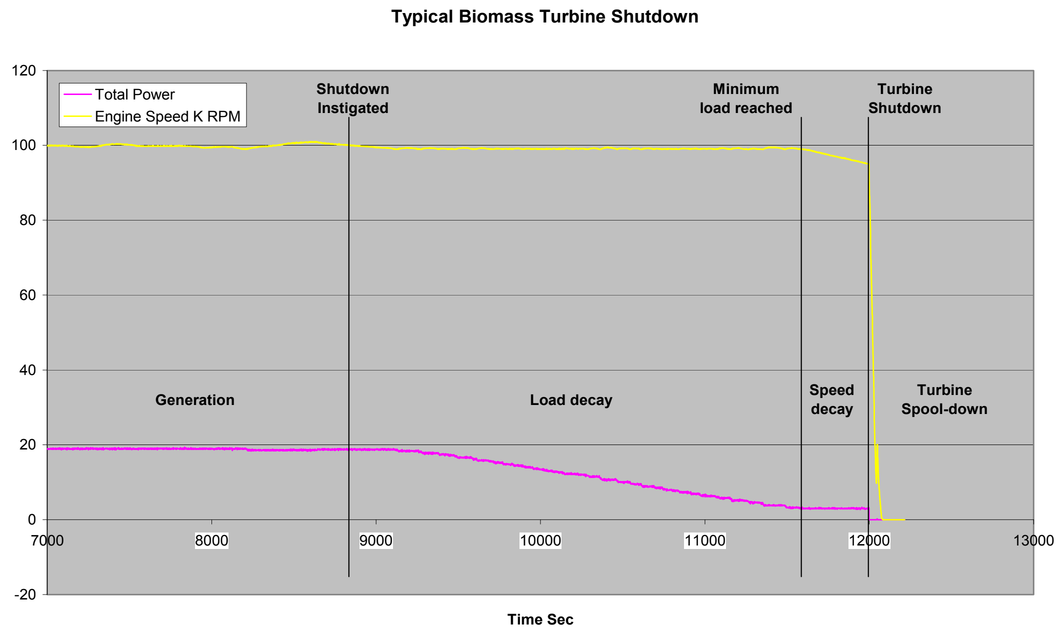


Fig 3.2 Typical turbine shutdown speed response

3.7 Emergency Shutdown Procedure

If a critical alarm is raised or the emergency stop is activated, the system must be stopped quickly. The control system halts the turbine and combustion immediately. The turbine is decelerated within 10 seconds and the ID Fan is stopped in approximately 30 seconds. The high temperature heat is contained in the combustor by the additional high temperature insulation. The natural draw of the chimney will vent heat slowly from the system. There will, however, be insufficient air for complete combustion. Therefore there will be visible emissions from the flue under this emergency condition. As soon as the combustion system is restarted, after the fault is cleared, the visible emissions will stop.

4. Long Term Testing

Once the commissioning was completed, a series of long term tests were conducted to achieve the 4000hrs run time. During these tests problem areas could be discovered and resolved, other areas are improved. The test unit is shown in Figures 4.1 and 4.2.

Fig 4.1 Views of the test set-up

During operation the turbine electronics were recalibrated and tuned to optimise output. The electrical loading rate of the alternator was optimised to give a controlled engine response and maximise electrical output. The combustion and grate system were modified to reduce heat loss and improve air flow and reaction rate.

Fig 4.2 View of combustor from feed side

4.1 Testing Schedule

4.1.1 Starting

The start procedure developed during the commissioning phase was tested over a year with over 100 successful starts. Various "lift points" were tested to determine the optimum conditions. Once the optimum conditions were determined, the system was subjected to cycle testing to prove repeatability. The start system was then tested once per week during normal testing operation.

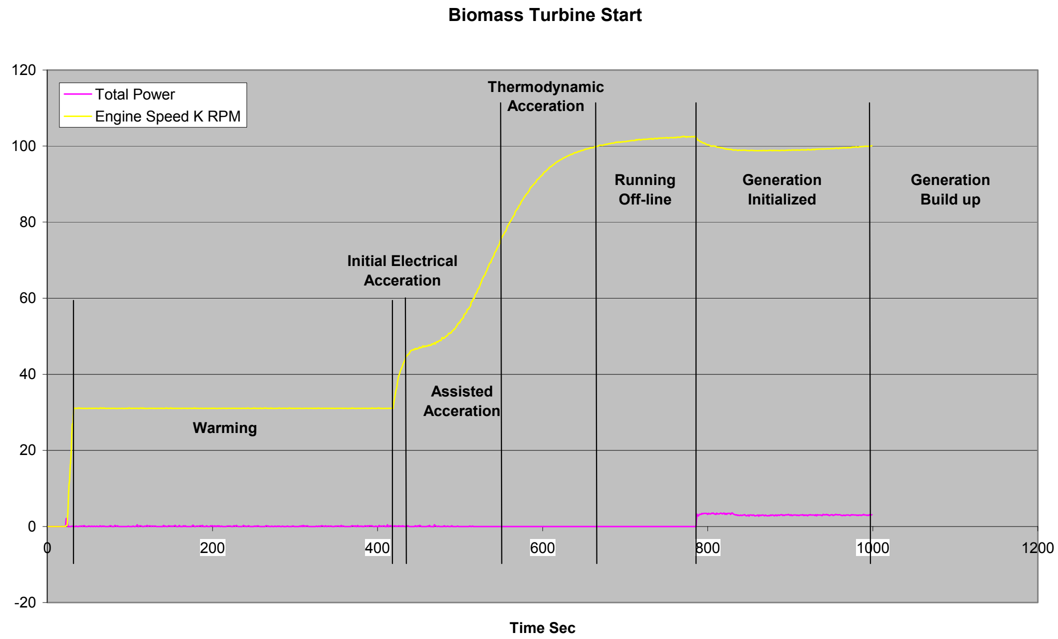


Fig 4.3 Start sequence

The above plot (Fig 4.3) is a typical start sequence recorded by the turbine's integral data logger.
The Biomass Turbine Start sequence can be broken down into 7 sections, which will be briefly described below:

Warming	The engine is run at low speed to gently warm the turbine and lubrication oil system.
Initial Acceleration	On reaching the lift temperature, full electric assist is applied, increasing speed.
Assisted Acceleration	Biomass power builds up, assisting the electrical and further increasing speed.
Thermodynamic Acceleration	Electrical assist is no longer required and is removed. The engine continues to accelerate towards generating speed.
Running off-line	The system is run at full speed without load to stabilise before applying the generation.
Generation Initialized	The generator performs checks on the grid, then synchronizes with the grid and begins generating its minimum load.

Generation build up	Generated power is increased with temperature.

4.1.2 Operation

Generator operation was conducted during a series of tests. Initial tests ran for a few hours before shutting down. The later testing was operated continuously; 24 hours a day for up to 7 days. The longest single test was 14 days continuous operation. During the testing program the biomass generator has achieved a total of 4680 hours operation. Turbine inlet temperatures were limited by Bowman to 800°C.

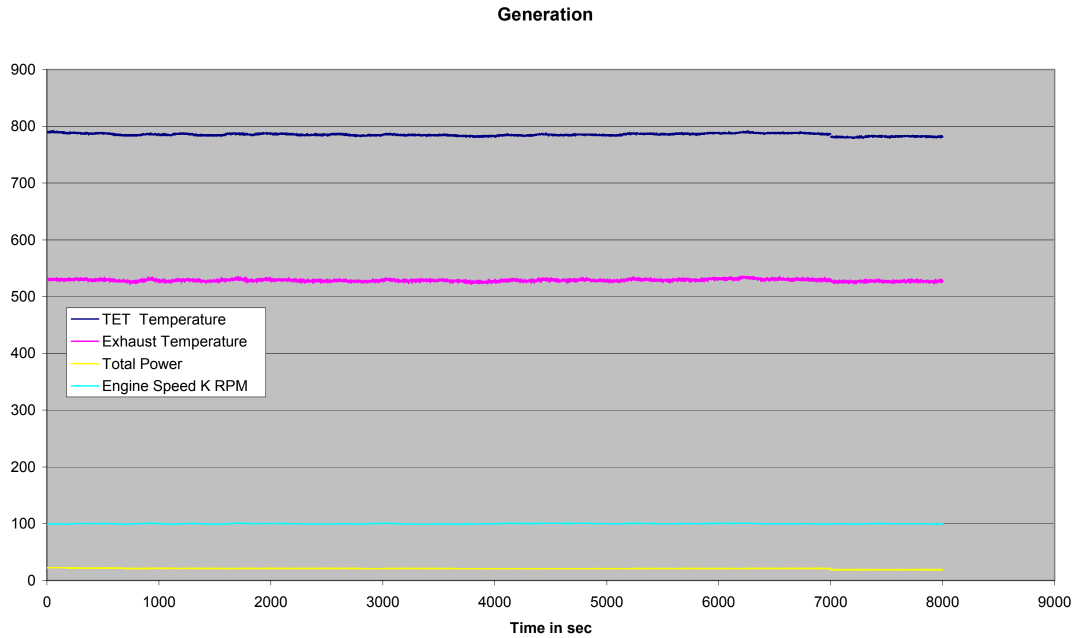


Fig 4.4 Typical generation

Combustion with full recuperation was stable and predictable. During the operation of the biomass generator, the combustor could oscillate the set point by 20°C without affecting the generator's output power, see Figure 4.4. The response for the combustion system at generation was slow with an added delay term. Very slow feed rates were needed to avoid temperature overshoots. The controller was tuned to the system but the feed rate ratio also needed gearing down. Step inputs when increasing the power could cause temperature overshoots, so additional temperature control logic has been added to contain these.

Fig 4.5 Combustion chamber

4.1.3 Performance Testing

During the testing schedule measurements of performance were recorded by the data logger, shown in Figure 4.6, and on daily test sheets as a back up. Once the system had reached steady state fuel consumption was metered over 24 hour periods. Average consumption was 37kg/hr of wood fuel with a lower calorific value of 3.6kW/kg hr, giving a heat input value of 133kW. Average power output over the same period was 20kW; therefore the overall electrical efficiency is 15%.

Fig 4.6 Photograph of generator & data logging PC

4.1.4 Run Hours

The system has run for over 4000hrs, producing between 20 –30kW in a very stable and reliable manner.

Summary break down of run hours:
- 160 hrs were completed during the initial commissioning, to achieve generating speed, testing and developing the start up procedure
- 240 hrs Operation at FSNL before generator commissioning, testing stability for generation
- 380 hrs Operation while commissioning the generator while running at minimum load
- 350hrs New Engine Commissioning, load was increased to 12-15kW over testing period
- 280hrs Loading trials, increasing output to 35kW
- 2990hrs extended generation to achieve 4000hrs total run time
- 160hrs were added during further emission testing
- 400hrs testing the CHP component

Total hours are 4680 to date

4.1.5 Maintenance Schedule

Cleaning and ash removal was carried out every 2 weeks. The system was shut down and allowed to cool. Due to the higher temperatures of combustion some ash melting was evident; however these were easily broken up and removable. Fan bearings were replaced.

4.1.6 Fault History

A power relay failed causing IGBT burnout; the system shut down safely. The system was fitted with a power relay that had been superseded by a newer design. The old relay was replaced with the new design and no further failures occurred.
An air lock valve failed, the control system detected the reduction in firing and shut down safely. Faulty parts were replaced. A grid spike caused a system shut down; the system restarted OK.

4.1.7 CHP Hot Water

Waste heat gases from the flue can be captured to produce hot water for heating buildings etc. The system was first run without a CHP boiler for its 4000hr testing so it would not interfere with the generator's testing. During this time emissions and temperatures of flue gases were measured. After the generator testing was completed, a waste heat boiler was fitted to the system.

The boiler was mounted on the combustor exhaust flange before the ID Fan and chimney. This also reduced the power consumed by the ID fan by 2 kW due to the combustion gases being cooler and therefore denser, requiring less volume to be drawn through for the same mass flow rate. A simple pipe work system was installed to circulate the hot water and dissipate the heat. This consisted of three hot water heat dissipaters, each fitted with a circulation fan and temperature thermostat to regulate the return temperature. In addition a centrifugal circulation pump with a flow rate of 1kg/s was fitted with a control valve up stream to regulate flow rate. Thermal expansion of the hot water is catered for by an expansion/accumulator vessel. A heat meter, pressure gauges and thermocouples were added to record conditions. The system was then filled and pressurised to 1 bar g and vented of air. See Figure 4.7.

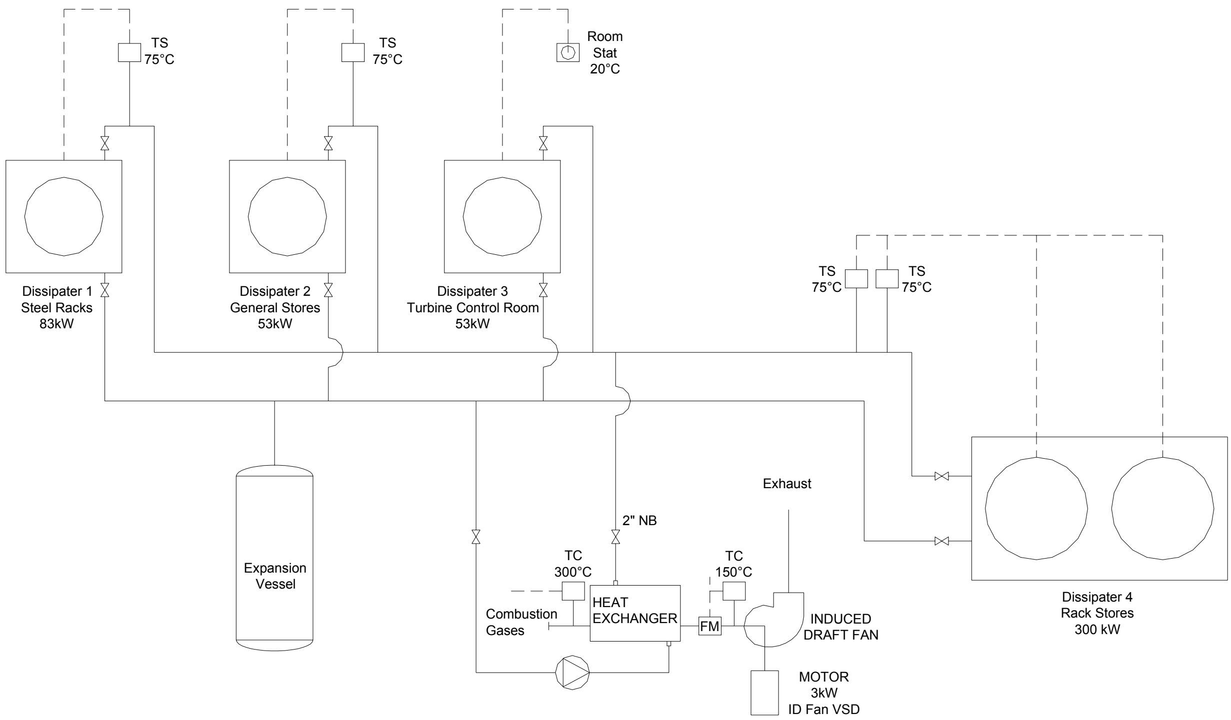


Fig 4.7 CHP pipe work layout

4.1.8 Testing the CHP

The pump was switched on and regulated to 1kg/s. The Biomass Generator was then started as normal and allowed to stabilize for 24hrs. The water temperatures before and after the hot water boiler were measured at steady state, these were 80°C output and 60°C return. This 20°C temperature at 1kg/s gives 90kW. The combustion gases were 310°C into the boiler and 158°C to exhaust. By adding the 90kW to 20kW generated the utilisation efficiency for CHP was 82.7%. The system was run for 400 hours with the CHP system in use.

After the 400 hours the system was stripped down for inspection as part of the final inspection requirements to complete the project. On inspection of the boiler internals on the combustion gas side, a light build up of fly ash particles were present, these particles were easily removed by light brushing. The CHP boiler used had relatively tight passages which would block up over time if regular cleaning was not carried out. This would require monthly cleaning and the installation of cleaning access points to the final design. The design of the CHP boiler should also be modified to open up the tight passages.

4.2 Emission Testing

4.2.1 Introduction

Emissions were measured using various wood fuels, including wood pellets, wood waste chips and MDF dust. Below is a sample report from a test conducted using MDF dust. This fuel was chosen because it is one of the more difficult fuels to combust cleanly and therefore represents a worst case. This exercise consisted of the following tests carried out on the wood waste burner exhaust stack:-

1. Measurement of particulate emissions using BS3405 method.
2. Measurement of gaseous emissions using electrochemical sensors and gas detection tubes.
   Gases tested:-

   Carbon monoxide
   Oxygen
   Hydrogen chloride
   Hydrogen cyanide
   Formaldehyde

3. Measurement of total VOC emissions using absorption tube method.

This report gives full details of the methods used and the results found.

4.2.2 Summary of Results

4.2.2.1 Particulate Emissions

1st sample	93 mg/m^3
2nd sample	134 mg/m^3
3rd sample	60 mg/m3
4th sample	69mg/m3

Results expressed at standard temperature and pressure

4.2.2.2 Gaseous Emissions

Results varied within the following ranges.

Electrochemical sensor measurements:-

Carbon monoxide	50 - 90 mg/m^3
Oxygen	10 - 12 %

Gas detector tube measurements:-

Hydrogen chloride	5 - 10 mg/m^3
Hydrogen cyanide	0 - 1 ppm
Formaldehyde	1 - 4 ppm

Results expressed at standard temperature and pressure

4.2.2.3 VOC Emissions

Total VOC emissions	1st sample	5.0 mg/m^3
	2nd sample	2.0 mg/m^3
	3rd sample	3.4mg/m^3

Results expressed as carbon at standard temperature and pressure.

4.2.3 Particulate Samples – Further Detail

4.2.3.1 Monitoring Methods

The method used for the tests was as described in BS 3405. This is an "isokinetic" sampling method, designed to produce results accurate to $\pm$ 25% when the main procedural requirements are observed. Briefly, the method consists of using a calibrated air sample pump to draw air from within the exhaust duct, passing this through a pre-weighed filter which is re-weighed at the end of the sampling period. The increase in weight of the filter divided by the volume of air sampled gives the particulate emission concentration.

The equipment used and the detail of the method as set out in BS3405 are all designed to ensure the accuracy of the result. The two main elements of the method, which contribute to this accuracy, are the selection of the sampling *location* and the *rate* at which air is drawn through the inlet nozzle of the sampling train.

The sampling location is selected to ensure that air flow through the exhaust duct is as even as possible. The location must be away from the fan or any bends in the ductwork and preferably in a vertical direction. The sampling rate is selected such that air enters the inlet nozzle of the sampling equipment without changing velocity (the so-called "isokinetic" condition). The diameter of the nozzle and the rate of the sampling pump are adjusted to achieve this condition. The final results are corrected to allow for the actual temperature and pressure of the emitted air, thereby giving results quoted at standard reference conditions.

4.2.3.2 Sampling Equipment

The Negretti Isokinetic sampling kit was used. This consists of the sample probe with 37 mm filter holder. The kit was used in conjunction with a Charles Austin B100 diaphragm sample pump, a water trap and a Platon flow meter, all connected using flexible tubing. See Figure 4.8.

The equipment is capable of sampling at rates up to 16 litres of air per minute. By using 3, 4 or 6 mm diameter inlet nozzles this allows isokinetic sampling up to 40 m/sec duct velocity.

Duct air velocity was measured with an Airflow Developments pitot tube connected to a Digitron P200UL micromanometer. Duct air temperature was measured with a Testoterm thermocouple type thermometer, duct static pressure with the Digitron micromanometer. The sample filters were weighed using a Sartorius analytical microbalance.

4.2.3.3 Method Detail

A suitable monitoring location is identified and monitoring ports consisting of 50mm diameter holes cut in the ducting. These are fitted with blanking plates on completion of sampling. The temperature of the emissions is measured across each sampling diameter and checked to ensure an even profile to within the requirements of BS3405.

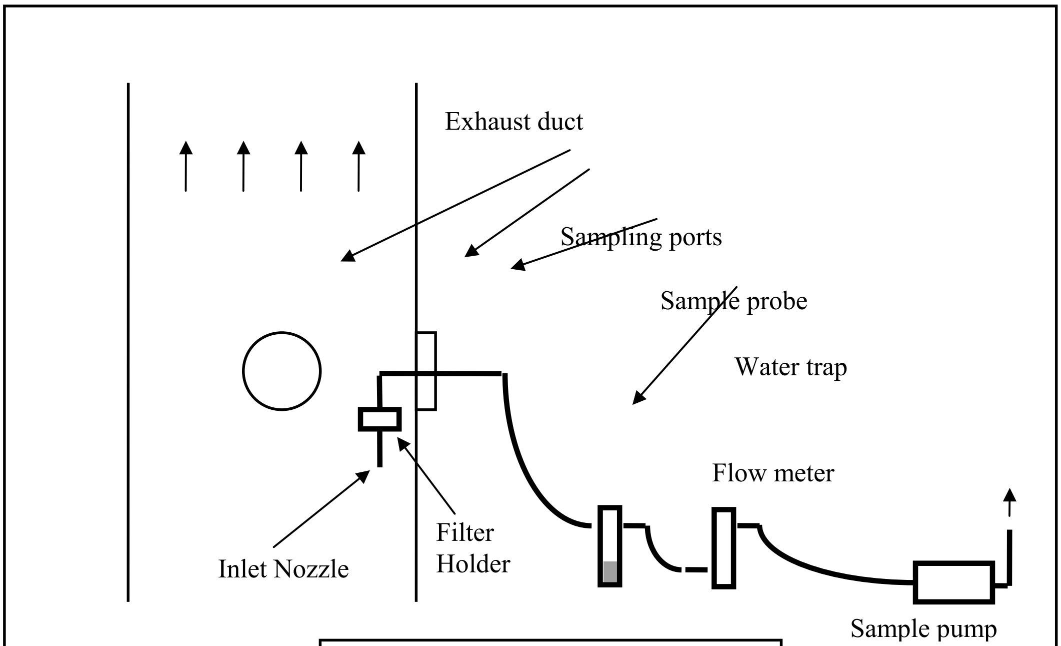
The pitot tube and micromanometer are used to measure the velocity profiles across the two sampling diameters, with ten measurements on each diameter. The figures are checked to ensure the velocity profile is constant to within the requirements of BS3405; the sampling nozzle diameter and sampling rate are then calculated.

Whilst taking the velocity measurements, the angle of the gas flow within the duct is checked to ensure that it is not more than 20° from the axis of the flue. The angle of the gas flow is shown by the angle of the pitot tube which creates the maximum velocity pressure. A pre-weighed sample filter is taken from its protective holder and fitted in the sample probe.

Sampling is carried out at each of the four sampling locations (Figure 4.8b), five minutes at each location, 20 minutes total for each duct, sampling at the isokinetic rate calculated from the velocity measurements. Sampling is cumulative on one sampling filter. The burner is arranged to continue running at a representative rate throughout the 20 minute period.

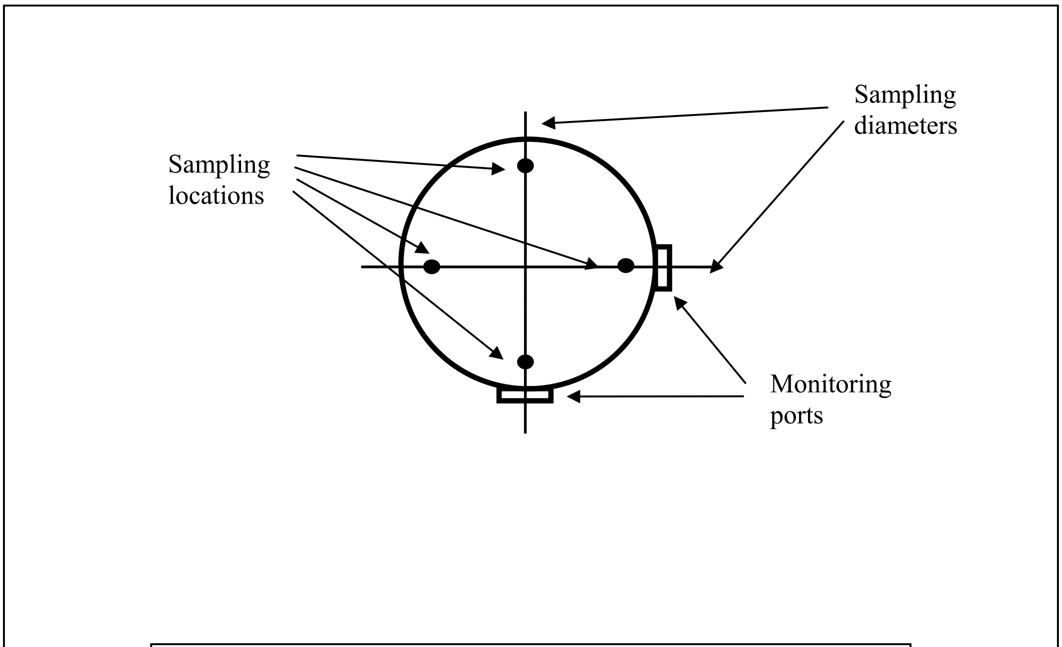
The velocity and temperature profiles are re-checked on completion of sampling to ensure that there has been no significant change.

The sample filter is replaced in its protective holder, identified and returned to the laboratory for re-weighing. From the increase in weight of the sample filter and the volume of air sampled, the concentration of particulates in the emitted air is calculated. The result is then corrected to the standard reference conditions of 273° K and 101.3 Pa.



SCHEMATIC OF SAMPLING TRAIN

(a)



PLAN OF SAMPLING PLANE AT MONITORING LOCATION

(b)

Fig 4.8 Schematics of particulate sampling equipment

4.2.4 Gaseous Emissions - Further Detail

Electrochemical sensors were used to measure concentrations of carbon monoxide and oxygen in the exhaust emissions. The instrument uses an air sample pump to draw a sample of the flue gases from the exhaust stack. These are cooled to ambient temperature and passed across the sensors; a direct readout of the gas concentration is given on the display.

The instrument used was the EMC Flue Gas Analyser. The sensors were calibrated prior to the exercise using standard calibration gas mixes supplied by SIP Ltd.

As would be expected, the instrument readings for the two gases tested were not constant. The results quoted in 4.2.2.2 show the range of variations over a period of one hour of continuous operation of the burner.

Gastec gas detection tubes were used to measure the concentrations of hydrogen chloride, hydrogen cyanide and formaldehyde.

The tubes are specific to the particular gas under test. The tube contains chemicals which react with the gas; the reaction produces a colour change. A manually operated pump is used to draw a 100 ml sample of gas from the exhaust duct. As this passes through the detection tube the colour change spreads down the tube according to the concentration of the gas under test. On completion of sampling the gas concentration is read from a scale printed along the length of the tube. The measurement is effectively a "spot check" of the gas concentration at the time of the measurement. A series of measurements are made to obtain a range of readings from which an average can be calculated if required.

4.2.5 VOC Emissions - Further Detail

Volatile Organic Compounds (VOCs) were measured by collection on carbon absorption tube with subsequent analysis in a Namas accredited laboratory using gas chromatography with FID detector (Note: Methane is not absorbed on carbon and will not be included in this sample result).

A stainless steel sample probe was inserted into the exhaust duct. An SKC low flow sample pump running at 100 ml per minute was used to draw air through the probe. The sample probe was of sufficient length to allow the sample to cool to ambient temperature. The sample was passed through an SKC 226-01 carbon absorption tube, which absorbs any VOCs present. Sampling was carried out over a 60 minute period.

On completion the sample tube was sealed and submitted to the laboratory for analysis for total absorbed volatile organic compounds.

The result quoted in 4.2.2.3 shows the average emissions over the 60 minute sampling period.

4.2.6 NO_x Testing

Exhaust gas emission mainly includes oxides of carbon monoxide (CO), unburned hydrocarbons, nitrogen (N_2) and particulates. Carbons are produced from the fuel during the combustion process, carbon dioxide (CO_2) is the main gas produced as a result of this. If there is insufficient air this part of the combustion process will be incomplete leaving carbon monoxide and unburned hydrocarbons. Providing the correct amount of secondary air will reduce these CO and unburned hydrocarbon emissions.

Nitrogen oxides consist of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), they are commonly referred to as NO_x. Nitrogen oxides are produced at high temperatures during the combustion process. This is caused by a chemical reaction between oxygen molecules in the combustion air and nitrogen in the fuel or present in the combustion air. Therefore even pure fuels such as methane which contain no nitrogen will produce NO_x emissions.

The maximum temperature of combustion will have a significant effect on NO_x levels produced during combustion; the higher the temperature the higher the levels of NO_x.

Options to reduce NO_x emission:
- Reduce Combustion Temperature
- Water Injection
- Exhaust Gas Recirculation
- Catalytic converter Equipment

The main objective of these tests was to determine NO_x levels; O_2, CO and CO_2 were measured to ensure combustion was in keeping with previous results. The hexane meter was only included to prove no hydrocarbons were included in the products of combustion.

4.2.6.1 Machine description

The emission measuring equipment is from ADC and was calibrated and certified prior to testing. The equipment comprises five parts, the pump which extracts the air from the exhaust and pumps it into the different meters and there are meters for carbon monoxide, carbon dioxide, hexane and nitric oxide. An additional Servomex O_2 analyser by Sybron Taylor was used to measure O_2 levels in the exhaust.

4.2.6.2 Test Procedure

The combustion system was warmed up and allowed to stabilise before readings were taken. Readings of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO_x) and hexane (C_6H_{14}) were taken every few minutes. The generator was then pre-warmed in order to get readings from a full load steady run. The results were plotted against time. Graph Figure 4.9 shows the variation of NO_x over the samples taken. After each reading the measure devices have to be purged of any remaining gases and then be reset to zero

4.2.6.3 Measured emissions

The readings of NO_X ranged between 2 and 10 ppm. Below is a graph of the results, samples were taken approximately every minute. The cycling of the readings can be attributed to movements in the fuel pile as new fuel disturbs the pile causing temperature fluctuations.

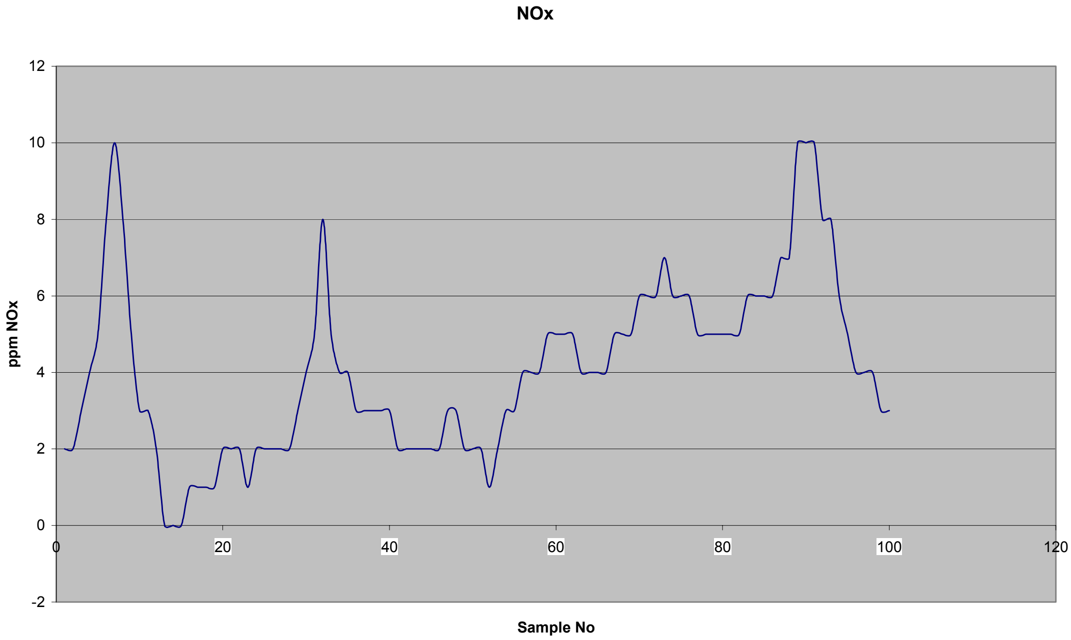


Fig 4.9 NO_x levels

4.3 Turbine Strip down report on Elliott TG50 Engine

4.3.1 Introduction

The engine was stripped after running to investigate the condition of the blades and vanes.

Previous runs with the initial engine had shown severe erosion of the turbine wheel leading edges. This erosion was believed due to weld debris left in the heat exchanger being pushed out at high airflow conditions. Any over-temperature, which was known to have occurred during initial running, would have exacerbated the erosion due to the lower strength and hardness of the hotter metal. Another cause could have been inadequate inlet filtering, but this was much less likely.

The highest velocity regions in the turbine flow path are at the compressor wheel inlet and exit and the turbine wheel inlet and exit. The regions which would be expected to see most erosion would be the compressor blade leading edges, the diffuser vane leading edges, the nozzle vane trailing edges and the turbine wheel blade trailing edges.

The turbine wheel blade inlet can also experience problems because any particles present are thrown outwards into the nozzle vanes but swept back into the wheel. Any particle can therefore make multiple impacts on the turbine wheel inlet.

4.3.2 Compressor End

The engine was stripped sufficiently for the diffuser leading edges and compressor wheel trailing edges to be visible. These are shown in Fig 4.10 and Fig 4.11 respectively. While there is evidence of the engine being run, there is no sign of erosion of the blades or vanes.

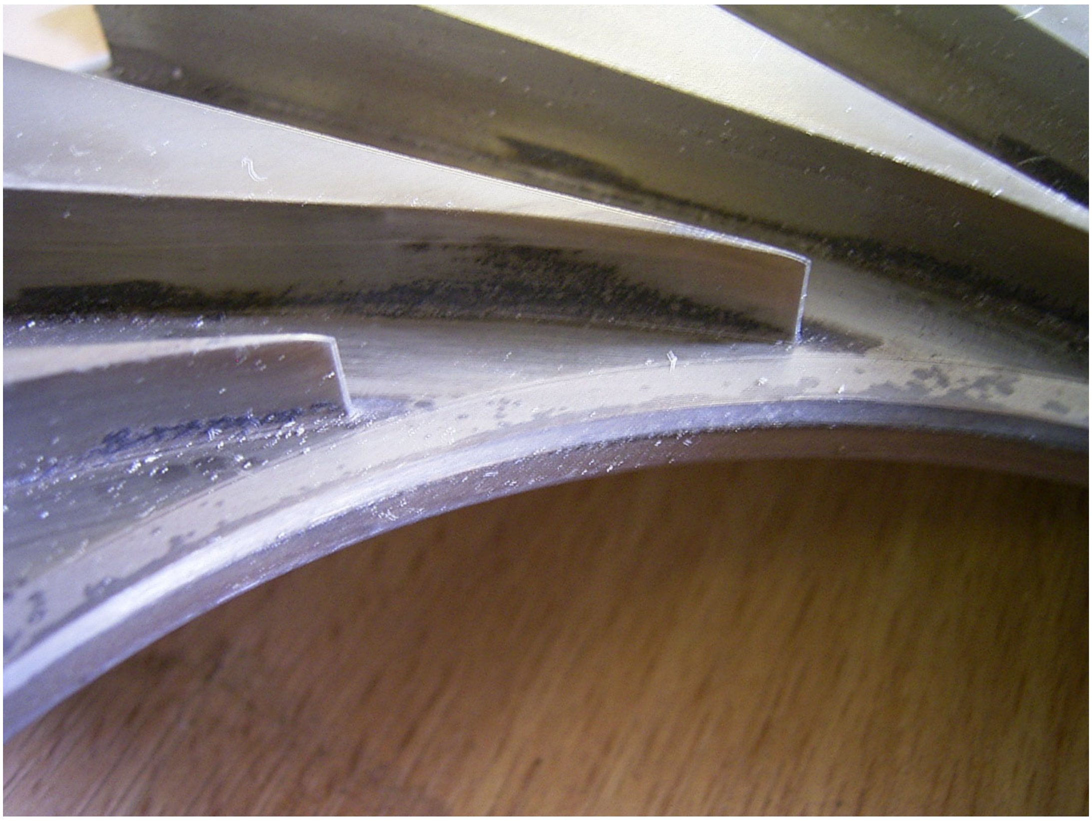


Fig 4.10 Compressor diffuser leading edges

Fig 4.11 Compressor wheel trailing edges

4.3.3 Turbine end

The nozzle trailing edges are shown in Fig 4.12

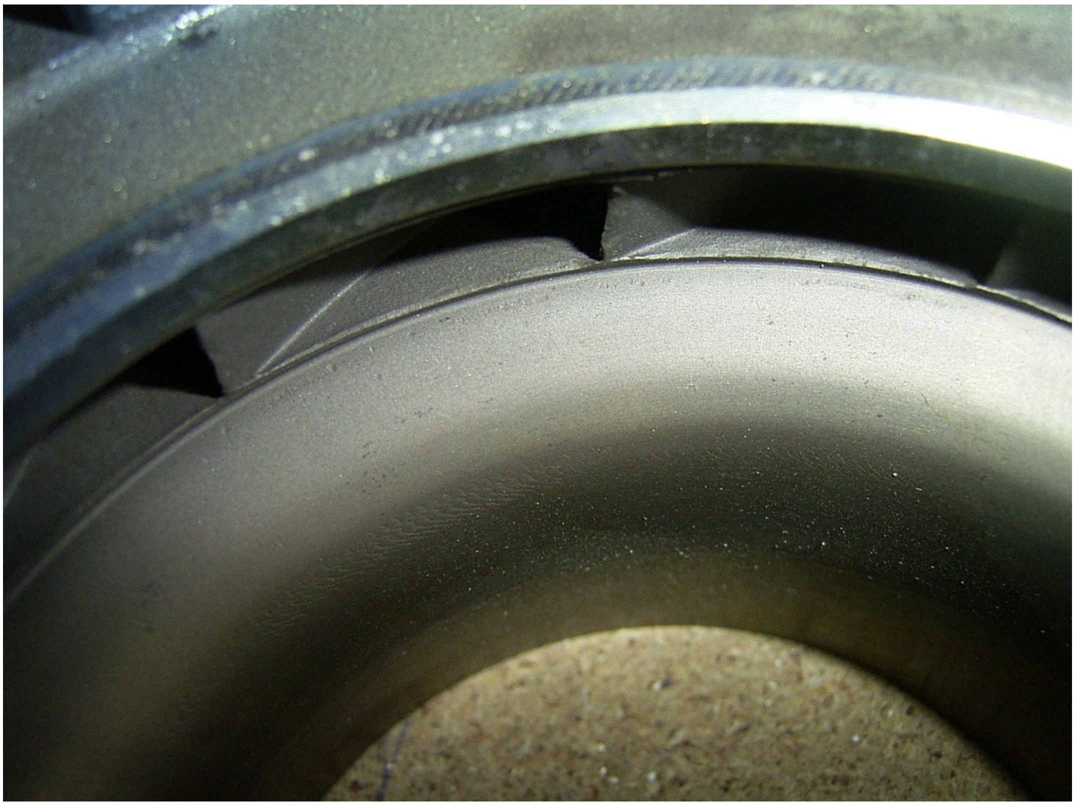


Fig 4.12 Turbine nozzle trailing edges

The nozzle trailing edges shown minimal signs of erosion with perhaps slight evidence for some rounding of the trailing edge corner (the highest velocity region). However there are no signs of the severe erosion seen on the initial unit.
The turbine wheel trailing and leading edges are shown in Figures 4.13 and Fig 4.14 respectively.


Fig 4.13 Turbine wheel trailing edges

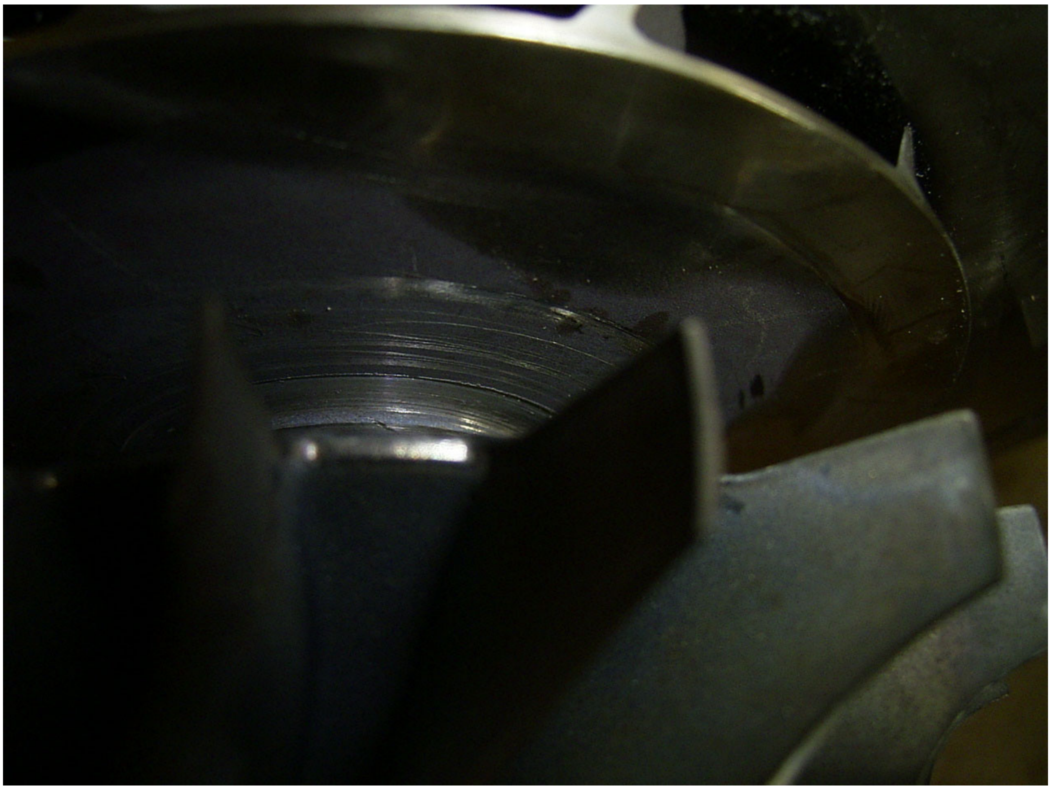


Fig 4.14 Turbine wheel leading edges

The turbine appears to be new except for some discoloration due to heat.

No problems with weld debris are apparent. The debris would be expected to be ejected during initial running when the heat exchanger reached full temperature and the air flow reached its maximum.

Other parts of the engine were found in good order.

4.3.4 Conclusions

1. The engine unit is in good order.
2. Inlet filtration does not appear to be a problem.
3. A system for cleaning the inside of the heat exchanger tubing and headers is required to avoid damaging the turbine during initial running.

5. Results & Discussion

5.1 Starting Procedure

The starting procedure has been developed and is now well proven with over 100 successful starts. This has involved numerous iterations of speed and temperature combinations to establish the optimum rate of acceleration time for the engine. An understanding of pressure and temperature requirements has been gained for each stage and speed of the turbine during starting. From this experience the process has been automated to reduce or remove operator intervention. Data logged during each start provides a reference point for future development and problem solving. This was a very important stage of development, successfully completing this task allowed the commencement of all other development activities.

5.2 Run Hours

The system has run for over 4000hrs, producing between 20 –30kW in a very stable and reliable manner. Testing began with the initial commissioning with the aim of achieving generation speed. Once this was achieved testing was focused on developing the start up procedure. The next stage was operation at full speed no load (FSNL) for a number of hours to establish system stability before generator commissioning could be started. The generator was then commissioned running at minimum load. The generator load was then slowly increased to 12-15kW during a testing period. Further generator loading trials aimed at finding the maximum power obtainable for the system increased output to 35kW. Testing was continued to achieve the targeted 4000hrs total run time. During the extended run testing the system was generating for up to 14days before ash removal. This period of de-ashing could have been extended further to an estimated 30 days based on the ash content of the combustion chamber. Additional operation was conducted for emission testing. A waste heat boiler was added to the system and tested to provide the CHP component data. Total operation hours are 4680 to date. Further hours are been logged with demonstrations to interested parties.

5.3 Measured Performance

During the testing and operation, data was obtained from the integral data logger and other independent instruments; all instruments were calibrated before testing. Combustion temperature was measured by two thermocouples and an average taken, a non-critical alarm would be raised if there was a high deviation between the readings. Combustion temperature during testing ranged between 900-1150°C. Turbine entry temperature was again measured with two thermocouples and directly logged. Turbine entry temperature during testing ranged between 700-

900°C. The three phase currents, voltages, frequency and power output by the turbine were measured directly by the integral electronics package. Other internal electronic signals used for monitoring the health of the turbine system were also measured and logged. The net electrical output ranged between 18-35kW_e. From the temperatures and mass flow rates determined, the heat exchanger efficiency was calculated to be 71%. This efficiency can be easily improved by increasing the surface area which will affect the costs; some improvements to the design are also possible. The exhaust gas temperature ranged between 300-330°C, this is used for CHP waste heat boiler. After the waste heat boiler the temperature was reduced to 158°C. This added 90kW of heat to generated electricity. The utilisation efficiency for CHP was thereby increased to 82.7%. These temperatures are reasonable but could be improved slightly. From the mass flow, ambient temperature, compression temperature and pressure ratio measured, the compressor isentropic efficiency of 62% was calculated. This figure was disappointing, but shows an area where the system could be improved. It is hoped future engines will have compressor efficiency around 78-80%. From the mass flow, ambient temperature, compression temperature and pressure ratio measured, the turbine isentropic efficiency was calculated to be 80%. This figure is reasonable but could be improved perhaps by 5%. Fuel consumption at steady state was measured by weighing fuel into a metering hopper. Calorific tests were conducted by Staffordshire University. From this information and the electrical output the overall efficiency was determined to be 15%. This figure is reasonable for a second stage prototype. By improving the engine cycle and heat exchanger performance, the overall electrical efficiency could be improved to around 25%.

5.4 Heat Exchanger Materials

Heat exchanger performance has been benchmarked and durability has been proven. Materials for the heat exchanger have been studied and results obtained from actual running. A sample of heat exchanger tubing that was subjected to combustion temperatures ranging between 900-1150°C was submitted for testing after 4000hrs operation in order that the depth of oxidation into the underlying steel could be evaluated. A polished section was prepared perpendicularly through the sample and examined using optical light microscopy. The normal oxidation thickness of the piece is in the range of 5μm to 20μm thick and has formed as a continuous dense oxide layer. Occasional masses of up to 130μm thick are formed at grain boundaries within the steel surface. Additional accelerated testing was conducted on control and powdered samples with similar gas conditions. These tests predicted a life expectancy of 100,000 hrs for the heat exchanger.

5.5 Recuperation

All of the waste gases from the turbine are reused in the combustion chamber, giving 100% recuperation. The high temperature return air still contains its 21% oxygen; therefore it can be used for the combustion requirements. The increased temperature of this combustion air requires less energy input to lift the temperature to the desired combustion temperature, reducing the fuel feed rate. Additionally the high temperature improves the reaction, as the combustion is already above the char ignition temperature. The system is therefore not reliant on reflected energy from ceramics to vaporize the moisture content and raise the char temperature for clean burning. Care must be taken when starting this system as char can be rapidly activated at the turbines lift points. This can rapidly increase the temperature of combustion to dangerous levels for heat exchanger life. This is currently managed by the operator for a commercial model; controls will be developed to achieve this. Harnessing 100% of the turbine exhaust energy is the major advantage of the indirect fired system.

System performance has been evaluated and benchmarked for further development.

5.6 Economic Analysis

5.6.1 Comparing the Indirect Fired Turbine with a Steam Based System

A 50kW$_e$ steam based system requires a biomass combustor, a waste heat boiler, a steam engine or turbine and a condensate package with CHP heat exchanger. A triple expansion steam engine would probably be the best choice in terms of costs and efficiency at this size; this would achieve an overall efficiency around 8-10%. Costs for this equipment package are £325,000 this works out at £6,500/kW. Maintenance costs for this system need to be added for yearly boiler insurance inspections, chemical dosing of feed water and higher supervision costs. Using a 7p/kW (including the ROC) this system would generate £28,000 over a year (based on 8000hrs/year), less £3,000 for maintenance, leaving £25,000. Therefore even with free fuel from a waste source it would take 13 years just to payback the initial investment costs. If waste removal charges of £40 per tonne were included, this would save £8,000 per year and reduce payback to 10 years. If a steam generation project had to purchase fuel, the low efficiency would mean a loss would be made over a considerable period. Current low electricity prices make biomass generation difficult, if not impossible, with steam at electrical outputs under 1MW.

Waste heat generated by the steam cycle must be removed; typically six times the electrical power needs to be dissipated in either CHP or to atmosphere. This large amount of heat often has no real use and is dumped to atmosphere. The available heat for CHP is from the latent heat of condensation, normally this is 100°C for an atmospheric condenser cycle. This can easily produce hot water around 80-90°C for heating.

Steam systems do become more efficient and cost effective with size, 1-2MW$_e$ systems can be offered at 20% efficiency with costs around £1000-1500/kW, although grid connection can be costly. Fuel transportation issues also need to be investigated as these add operational costs and reduce the environmental benefits. Generally generators under 250kW$_e$ can be connected to standard 415v 3phase supplies without special arrangements.

Our indirect fired system, now patented under No 01273128.7, re-uses all of the waste heat from the turbine cycle, therefore halving fuel consumption. The only energy allowed to leave the system is from the flue gases and casing losses. Therefore our indirect fired system will always be twice as efficient as a steam based system, with comparable engine efficiencies. Costs will be reduced for the indirect fired system as the system is simpler with reduced need for equipment. A 50kW IFAT system would cost around £200k for a full system, with an efficiency of 20%. A 100kW IFAT would cost £250k, with costs reducing £200k (£2000/kW) with volume production. Efficiency for the 100kW IFAT is expected to be 25%+, depending on the turbine used. In the future a 1-2MW indirect fired system could achieve higher efficiency with cost target around £1000-1500/kW.

By using direct combustion the widest range fuels can be used, as long as the combustion products are not harmful to the combustor and heat exchanger materials. Changes in calorific value are easily compensated by using over-sized grates and temperature controls. Changes in moisture content can be compensated for in the same way, although limits apply as the heat of the fuel is used first to evaporate the water, then the remainder is used in raising the temperature of combustion gases. Therefore if the moisture content (MC) is too high there will not be enough energy left to produce heat. Typically MC of around 20-30% is acceptable, dryer fuel gives a reduction in consumption rate, while an increase in MC will require more fuel up to maximum of around 60% MC.

5.6.2 Payback Period & Potential Income

Commercial and marketing research indicates a 100kW size would be the minimum size to be currently justifiable. The initial cost of a 100kW$_e$ biomass generator would be around £250,000. With flow line production the price is expected to drop to around £200,000 for each unit. This will produce 100kW$_e$, therefore in one year it will produce 800,000kWh of electricity. The electricity can be sold for 2p/kWh, in one year this will total £16,000. For each kWh, 5p can be received for the electricity producers ROCs; this will amount to £40,000/yr. Therefore the overall amount received for the electrical output will be around £56,000/yr.

With an efficiency of 25%, the system would earn a gross £75 per tonne of biomass used. Assuming an average yield of 12 tonnes per hectare and repaying the equipment over 10 years, this would earn the farmer £480 per year per hectare. A 100kW biomass generator would require just 62 hectares of energy crops, and would provide nearly £30k net income. When the advanced turbine cycle is completed and efficiency increases to 40%, the system would earn a gross £100 per tonne of biomass used. Based on the above, this would earn the farmer £640/year per hectare and require just 46 hectares of energy crops. The additional heat available could be used to provide a greater income, through grain drying, district heating or the reduction of moisture content for increased fuel efficiency.

Average wood working factories require between 200-300kWe to operate their machinery and produce 15-20 tonnes of wood waste per week, which costs £40/tonne to dispose of to landfill. Talbott's have over 3000 units installed using this waste to heat factories during the winter, but heat is not required during summer months. Therefore an opportunity exists to produce usable energy year round using existing infrastructure. The total cost for woodworking factories using wood waste to fuel the 100kW$_e$ system can be calculated by assuming a calorific value of 4kW/kg/hr and a fuel rate of 125kg/hr, it would cost £40/t (£0.04/kg) to send their wood waste to landfill. Burning the wood waste will lead to a saving of £5/hr or £40,000/yr. Their overall return would be the £56,000 for the electrical output and £40,000 disposal costs saved each year, equating to **£96,000/yr**, this would lead to a less than **3 year payback** period, plus free heat.

5.6.3 Carbon Savings

The Biomass Generator 100 produces around 100kW of electricity and approximately 150kW of heat.

The equivalent emissions from a local power station can be calculated thus:-
Average emissions from UK fossil fuel generators including transmission losses have been estimated at 183g/kWh.
Therefore: $100kW_e$ x 8000hrs/year x 183g/kWh = 146.4 tonne/year

The equivalent emissions from an oil-fired boiler can be calculated thus.
Average emissions from UK fossil fuel boilers have been estimated at 98g/kWh.
Therefore: $150kW_{th}$ x 8000hrs/year x 98g/kWh = 117.6 tonne/year

The total CO_2 emission reduction per year for each unit would be 264 tonnes.

(Calculation taken from DTI Energy Trends publication – Savings in Carbon Emissions from Combined Heat and Power (page 3) – October 2000 –
www.dti.gov.uk/energy/inform/energy_trends/articles/bpoct2000.pdf)

6. Conclusions

The conclusions of the biomass fuelled indirect fired micro turbine development project are:

- The start procedure has been established and proven with over 100 successful starts. An understanding of required system parameters for biomass turbine starting has been developed. The start procedure is repeatable and stable, allowing automation and therefore minimising training of operators.

- 4680 hours of turbine operation have been achieved to date, with the system operating continually for up to 2 weeks. Ash build up was slow, meaning the system could possibly operate for 4 weeks without shutting down for ash removal. Further development of our automatic ash removal system would allow longer operation still.

- The system has been tested and proven safe and reliable with predictable operation. The system does not require constant supervision. In the event of a fault the system always shuts down safely or operates in a safe mode without the need for operator intervention. Therefore the system can operate unmanned, reducing running costs significantly.

- The heat exchanger being used in the indirect firing system is now a proven concept. Thermal performance and high temperature heat transfer rates were established. Material studies were conducted and highlighted materials suitable for a design life of 100,000hrs operation. These studies were backed up by testing conducted on materials used during the system's 4000hrs plus operation.

- Fully recuperated operation has been achieved, in that all of the energy from the turbine exhaust is returned to the combustion chamber. This utilisation of the exhausted gases reduces fuel consumption significantly and therefore boosts the overall efficiency. Additionally, the high return temperature improves combustion performance.

- The high temperature combustion process results in efficient combustion and achieves very low emissions comparable to natural gas. The chimney exhaust shows no visible emissions, enabling use of this system in smoke controlled zones. Carbon savings of approximately 260 tonnes per year will assist with strategies for reduction of greenhouse gases.

- The commercial and technical basis for future development has been established. An understanding of the fundamental system dynamics has been gained that will allow better future development. The system performance can be improved by further development of the turbine and heat exchanger components.

- This system has provided a demonstration of a new and innovative biomass renewable power generation system in the UK. Feedback from visitors has been very positive.

The project has been very successful meeting the objectives fully.

7. Recommendations

The concept is now well proven the next logical step is to improve the system and build on our success.

Further improvements can be made to the system, these would include:

- Increase in heat exchanger and turbine efficiency. A simple method of increasing the heat exchanger efficiency is through scaling the design although this will impact cost.

- Engine efficiency, particularly on the compressor side, could be improved.

- Micro-Turbine availability has been reduced in the last 2 years, with many manufacturers halting production due to a weak market and sales. Securing a supply of a suitable engine is critical.

- Payback analysis of the Biomass Generator system indicates a 100kW size would be easier to justify.

8 Acknowledgements

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