CHP GAS TURBINE FUELLED DIRECTLY BY A BIOMASS GASIFIER

(GT Biogasifier)

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EXECUTIVE SUMMARY

This project was focused on the development of technically and commercially viable small (5 to 250 kWe) combined heat and power (CHP) plants involving a gas turbine fired directly by a pressurised biomass-fuelled gasifier followed by a cyclone combustor. Direct-fired systems avoid the complexity and cost of sophisticated heat exchangers and offer a strong opportunity for commercial exploitation. The project took state-of-the-art gasifier and combustor technology and advanced it with the aid of computational fluid dynamics (CFD) modelling.

The experimental facility with a pressurised gasifier and cyclone combustor firing a gas turbine powered generator of about 40 kWe was designed, the gas turbine part was built and ready for installation; the pressurised gasifier and cyclone combustor were constructed and low pressure commissioning had started. The facility was intended to research and establish the deposition, erosion, corrosion and performance parameters for a number of biomass fuels, define allowable operating temperatures (and hence efficiencies) and establish through modelling and experimental measurement, control and protection arrangements for a pre-production prototype unit utilising a robust low cost gas turbine generator. Preliminary dynamic modelling of most of the system was completed. Modelling of the combustor and turbine gas and particle flows was also an integral part of the project with a reacting flow model being utilised to assist in combustor design; the development of validated models were intended to be of assistance in the interpretation of the experimental results and in the design of the pre-production prototype. Four wood fuels, with their relatively low ash and alkali contents were identified and, depending on the success of the results with these fuels, experimental work with less benign fuels could have been included.

The commissioning was underway when it was recognised by the Commission and the Partners that it would not be possible to achieve the project objectives within the timetable and budget. Previously a revision to the project had been agreed with the Commission to respond to delays which had arisen in the first six months of the project. As a result, it was agreed that the project would be terminated.

This report describes the achievements, the problems and their underlying reasons and identifies a potentially useful way forward. In particular both a considerable amount of valuable hardware has been built and the underlying theoretical flow and dynamic models have been developed and partially validated. The market need for small scale, low cost, biomass gasifier based CHP systems utilising gas turbines, identified at the start of this project, continues to exist. The availability of both the hardware and the underlying capabilities should be of major use in an appropriate future project.

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1. INTRODUCTION

This document is the Final Report for Contract JOR3-CT97-0144. The contract work was terminated in September 1998 when it became clear that it would not be possible to achieve the planned objectives within the agreed budget and to the timetable. All further work except necessary communication with the Commission was stopped at that time. This was confirmed by the Commission with a formal notice of termination with effect from the end of November 1998.

This report includes the information required for Final Reports with descriptions of the project objectives and the technical work which has been achieved. It also contains a section which describes the progress which has been made, the reasons for failing to achieve the planned objectives, the consequences of this and the options available to take advantage of the substantial progress which has been made.

2. PROJECT OBJECTIVES

2.1. Overall Context

Both France and the USA derive more than 15% of their total energy from biomass fuels. Sweden hopes to increase utilisation of biomass to 28% of its total energy demand by 2000 AD. Biomass could produce 20% of the world's electrical power by 2050 AD, (Ref.1). If these forecasts are to be achieved, new agro-industrial economies will have to be created in third-world countries. In the UK, government figures show that willow and poplar could supply 30% of current demand; this equates to about 15 BECU of new plant. At the other end of the scale, in rural areas of northern Europe, many homes are heated by individual wood-burning boilers. If these units were coupled to small (5kWe) gas turbines to produce electricity as well as heat, investment costs could be recovered in less than 2 years. Useful updating and additional background information can be found in Refs. 2 and 3.

In the UK, the current combination of Set-Aside payments, Woodland Grant Scheme payments and Better Land Supplements, together with the NFFO, is producing a genuine opportunity for power crops, provided that the total cost of fuel plus power generation can be held to 0.06 ECU/kWh, with implied capital costs of 1000 ECU/kW(e) or less. These targets are certainly achievable with the proposed direct-fired system. It has been observed that UK plant might reach 1000 MW(e) pa by 2010, a plant cost of about 1000 MECU.

ETSU (UK) has reported on market opportunities for small-scale CHP in UK public, commercial and domestic buildings (Ref.4). The most important (relevant) finding was that a market existed for over 7000 installations of plant ranging from 15 to 50 kWe but that virtually no market penetration had been established. A further ETSU study (Ref.5) was limited to gas turbine based CHP in the UK. It identified a potential market for over 400 units of 250 to 500 kWe.

Apart from the sales of CHP plant and biomass fuel that should derive from this project, there are other, less tangible benefits arising from the intellectual property that will be created. European companies will be well placed to undertake design and consultancy work for foreign companies, sales of related software will increase, and customer training packages will be based on the simulator development. Finally there will be many opportunities for sales of ancillary equipment developed especially for this project, for example sophisticated plant control and simulation systems and also of validated CFD modelling software for applications in particle containing gas flows in gas turbines and combustors.

The primary incentive for the use of biomass in energy production is the need to satisfy increasingly stringent environmental standards. Biomass combustion produces 33% less SOX and NOX than fossil fuels and carbon dioxide emissions are environmentally neutral (Ref.6).

If the cost and performance targets are met, this project should create a huge new market for European industry, and many new jobs in agriculture. Large areas of farmland, now set-aside, will yield power crops and contribute to reduced levels of environmental pollution. Third world countries will be able to reduce expensive fuel imports.

Job prospects, particularly in SMEs, will improve in rural areas and technology will transfer downwards from aerospace industries. Investment will move from industries based on the reciprocating engine, nuclear and fossil-fired generation systems.

Small-scale distributed plants (Ref.7) will produce large quantities of high and low grade heat to rural and small industrial customers. New enterprises will be created to take advantage of this source of cheap energy. High intensity farming methods that are presently marginal have the potential to become more viable.

2.2. Project Technical Approach and Objectives

The project is focused on the development of technically and commercially viable small (5 to 250 kWe) combined heat and power (CHP) plants involving a gas turbine fired directly by a pressurised biomass-fuelled gasifier followed by a cyclone combustor. Direct-fired systems avoid the complexity and cost of sophisticated heat exchangers and offer a strong opportunity for commercial exploitation. The project takes state-of-the-art combustor technology and advances it with the aid of computational fluid dynamics (CFD) modelling so that the gas stream entering the turbine contains less than 1 ppm alkali and 10 ppm particulates of a maximum size of 5 microns. Turbine inlet and exhaust temperatures will be 850 and 600 °C respectively; gasifier/combustor pressure 3 bar(a) with gas leakage <2%. NOX is targeted at <90 vpm (15% oxygen).

The experimental facility with a pressurised gasifier and cyclone combustor firing a gas turbine powered generator of about 40 kWe was been designed and construction of the components parts largely completed. It was planned that this facility would be used to research and establish the deposition, erosion, corrosion and performance parameters for a number of biomass fuels, define allowable operating temperatures (and hence efficiencies) and establish through modelling and experimental measurement, control and protection arrangements for a pre-production prototype unit. Preliminary dynamic modelling of much of the system was completed. Modelling of the combustor and turbine gas and particle flows are also an integral part of the project with a reacting flow model being utilised to assist in combustor design; the development of validated models will be of considerable assistance in the interpretation of the experimental results and in the design of the pre-production prototype. Four wood fuels, with their relatively low ash and alkali contents were to be utilised initially and experimental work with less benign fuels was potentially possible.

In an attempt to recover the programme when it became evident that the gasifier / combustor part of the development was behind programme after about six months due to a completely new design, a revision to the Technical Annex was proposed to the Commission and received their approval.

The gas turbine part of the system was commissioned early in 1998 but delays and difficulties, which are explained in detail later in the report, in the commissioning of the gasifier / combustor led to the recommendation that it would not be possible to complete the project within the timetable and budget available.

3. TECHNICAL DESCRIPTION

In this Section, programmes and timetables refer to the revised Technical Annex unless explicitly stated otherwise. A more detailed description of the work carried out by dk-TEKNIK is given in Annex E.

3.1. Critical Overview

3.1.1. Facility Design (Task 1)

3.1.1.1. Task Status

The Task is divided into three stages to cover (a) the initial design, (b) any changes to the design following commissioning (deliverable 1/5), and (c) final changes, following completion of the experimental programme, regarded as necessary to achieve the full objectives of this task as stated in the original proposal document (deliverable 1/6). Stage (a), which was expected to require 90% of the planned effort, was completed (deliverables 1/1, 1/2a, 1/2b, 1/3a, 1/3b,) thus satisfying the requirements of Task 1 insofar as the 6 and 12 month milestones were concerned. The remainder of Section 3.1.1 of this Report constitutes the “Design Intent Report” (deliverable 1/4(6)).

There are several reasons why this task took longer to complete than originally envisaged but, undoubtedly, the most important reason is the exceptionally ambitious nature of the project. The scale of the undertaking can most readily be appreciated by witnessing the size and complexity of the plant assembled at Risø (Denmark). The increased effort allocated to this task, and the high component and constructional costs, have resulted in considerable additional (unplanned) costs to two of the three partners (dk-TEKNIK and J.E.T.).

Other reasons for the delay include a number of changes to the overall plant layout. It was agreed, for instance, to replace the deposition, erosion and corrosion (DEC) loop by inspections of DEC within the turbine. The involvement of the Danish licensing authority (AT) influenced the design and interconnection of all pressure vessels and pipework, including the turbine bypass valve, the location of the kerosene burner and other control and safety features. Unfortunately, the need for some of these changes was not recognised until after certain components had been designed, procured and fabricated according to the originally agreed schedule. There is, however, little doubt that the design benefited from some of the changes.

3.1.1.2. Conceptual design and outline specification

The experimental facility features a grate gasifier coupled to a high temperature cyclone combustor exhausting to a gas turbine and alternator. The gas turbine compressor is used to pressurise the entire system. The facility is designed to achieve the following performance targets:

- Turbine inlet temperature: <850 °C, exhaust temperature: <600 °C (steady state).
- Gasifier/combustor pressure of <3.2 bar(a).
- Operation with four wood based fuels.
- Whole plant control and safety system.
- <10 ppm particulates of maximum size 5μm at turbine inlet.
- Alkali in the gas stream <1 ppm at turbine inlet.

A key feature of the design of the facility is that the turbine is capable of independent operation by virtue of a separate (liquid) fuelling system. This will facilitate start-up of the plant. The gas turbine is a modified Rover AAPP unit which incorporates its own kerosene combustor. The turbine stages are readily accessible for direct inspection of DEC damage. The gasifier and cyclone combustor designs are adapted from units which have been developed and operated by dk-TEKNIK, and have benefited by design improvements resulting from the computational fluid dynamic modelling undertaken as part of this project.

The provision of effective gas cleaning with low pressure drop is resolved by the gasifier. There would be no attempt to utilise the waste heat, but its quality, quantity, and chemical characteristics (deposition and corrosion potential, NOX level) was planned to be measured.

The design achieves a plant control system, with diverse safe shut-down features which ensure that the gas turbine cannot be oversped even under the most extreme fault conditions. Reliable, fast acting valves provide independent control of the gasifier and combustor and the gas turbine during start-up and shutdown, and as protection for the gas turbine under fault conditions. A variable electrical load bank is used to test the control system under transient and fault conditions.

The final layout is shown in Figure 1. It is generally simpler and more compact than the original concept, and is capable of continuous (rather than batch) operation. It has also been shown to satisfy all the essential requirements of: start-up, shut-down, and emergency trip procedures. The final design represents an enhanced and more economic design that could bring down the price of a commercially traded plant. Figure 1 also shows the individual responsibilities of J.E.T. and dk-TEKNIK for delivery of plant items.

It is worth to take notice of the size of the cyclonic combustor. It is around a 100 times larger than the standard kerosene combustor that normally runs the turbine and it has a thermal mass that exceeds this number many times. The reason for this is to ensure:

- Proper retention time to secure burn out of heavy tars and carbon particles carried over from the gasifier
- Ceramic lining to maintain stable temperature
- Particulate retention due to an advanced cyclonic CFD modelled design that acts as a dust collecting cyclone thus avoiding complex and expensive Hot Gas Filters featuring high operational costs.

3.1.1.3. Gasifier, combustor and pressure circuit

The design, Figures 2(a), (b), and (c), comprises an enhanced gasifier based on earlier dk-TEKNIK designs but equipped with newly designed air distribution nozzles. The fuel auger was changed from a screw auger to a triangular shaped reciprocating fuel auger traditionally used in wood chip plants.

The gasifier is mounted on skids inside the horizontal pressure chamber. It is connected to the fuel locker system via a smaller fuel bin. The fuel auger runs back and forth at the bottom of the fuel bin. The bottom of the gasifier consists of a fixed step grate equipped with air inlet holes. The gasifier air is controlled by a set of valves that can control the exact amount of air required at different parts of the grate. This is vital as it must be possible to control the reactions in every part of the grate to maintain stable (and low) gasification temperatures in order to reduce, or avoid, evaporation of alkali metals. Three thermo-transmitters are present in the fuel layer, situated on the fuel auger. These transmitters are important with respect to the control of gasification air and, hence, control of the gasifier temperature.

The gasifier pressure vessel is connected to the combustor pressure vessel by an expansion bellows unit to reduce system stresses acting on the pipework and terminal welds.

Design of the combustor started with a literature study covering enhanced cyclone combustor geometry. The resulting outline design was delivered to Numeca for initial modelling and validation before finalising the design. A debris trap, required to protect the gas turbine from ingested refractory material, was initially incorporated in the top of the cyclone combustor. However, after changing the cyclone outlet cone to high temperature stainless steel, the debris trap was discarded. The change to stainless steel is possible as the temperature distribution calculated from the CFD modelling by Numeca shows that the metal will be protected by a thin layer of “cold” air coming from the top air inlets in the cyclone combustor wind box.

A further requirement of the combustor is that it should be capable of dual-fuel operation, so that kerosene can be used for start-up, pressurisation of the gas circuit, and pre-heating the cyclone combustor. It may also be necessary to use a small flow of kerosene for speed control and coping with load transients. Several possibilities were considered but it was finally decided to adapt the standard burner supplied with the Rover GT. The concern then changed to where the burner should be located and how to ensure that the air-fuel ratio could be held within the necessary limits to produce complete combustion of the kerosene. The final configuration has the burner bolted into the top (outlet) of the cyclone combustor in such a way that the mass flow of air through the burner never falls below 66% of the total mass flow through the whole pressure circuit. This provides sufficient air to ensure full combustion of kerosene under all conditions and should therefore minimise the formation of carbon deposits within the burner. Furthermore, the unburned air in the burner outlet will mix with the exhaust gas from the cyclone combustor thereby diluting it and reducing its temperature before it is conducted to the gas turbine.

Glow heads from a diesel car have been installed in the cyclone walls in order to ignite the producer gas from the gasifier.

The final design of the plant has been developed under constant vetting by the safety and health authorities in Denmark (AT).

General assembly and manufacturing drawings of the gas turbine and alternator framework and the interconnecting pipework were completed to schedule but changes were subsequently required to the turbine inlet and compressor outlet. One of the requirements from AT was a design that would not expose high temperature metallic pipework to pressure differences of more than 100 mbar from the inside. The final arrangement involves a single coaxial connection between the gas turbine and the cyclone combustor. This arrangement virtually eliminates concern over creep failure, due to dramatically reduced metal temperatures for the outer, pressure containment, pipe. The hot inner pipe is allowed to expand more than the outer pipe, and the outer pipe will be anchored with respect to the turbine frame (Figure 3). This new configuration for the turbine inlet pipework virtually precludes the use of a hot gas bypass valve, thus overspeed protection would be provided by a blow-off valve in the compressor outlet.

The whole rig will be mounted on a steel frame and a scaffold, for operational and maintenance access, will be built around the rig.

An important discipline during the design phase was to check the capability of the design against projected operational procedures to ensure that the design allowed the plant to be started and operated satisfactorily under all anticipated conditions. This led to a number of important changes including, for example, the substitution of a powerful programmable drive unit for running the alternator as a starter motor.

These operating procedures, which have since been incorporated in the “Design and Operating Manual” (see later) but the following example serves to illustrate the methodology:

Pre Start-Up Valve Settings

1. V_{Blower} closed
2. V1 open (start-up heater)
3. $V2_n$ to preset start up position (grate valves)
4. V4 closed
5. Check V4 flow setting
6. $V4_{by\text{-}pass}$ open
7. V5 to preset start up position
8. V6 closed
9. $V_{stopcock}$ closed
10. Electric load bank off
11. Zero excitation on alternator
12. Manual kerosene spill valve closed

Start-Up Procedure on Kerosene

1. LP fuel pump on
2. Back-drive GT
3. Ignite at 200Hz followed by automatic acceleration to 250Hz
4. Open $V_{stopcock}$
5. Within 10s ignition should be achieved, or the start-up should be aborted.
6. When self-sustaining conditions are reached at 250 Hz, backdrive disengages automatically and GT accelerates automatically to full speed (400 Hz).

3.1.1.4. Wood fuel feed system

Wood chips and pellets are delivered to the gasifier bed via a pressurised lock hopper. The lock hopper system is made of two manually operated "spade valves". The fuel feed to the gasifier is not governed by the lock hopper system, rather by the fuel auger working at the bottom of the fuel bin. The rate of fuel feed is governed by the fuel auger speed and by a fuel layer thickness control spade. The fuel auger fulfils the multiple functions of: fuel feeder, internal fuel transport "ram" on the grate, and ash discharge "ram". It can only operate on solid fuels at the size of wood pellets or sized wood chips. It is, however, a system based on wood-chip boilers and has been working well for several years in wood chip district heating boilers and similar.

3.1.1.5. GT System including alternator and load bank

The gas turbine console is in two parts, Figure 4. The upper half is supplied with the Rover engine but the lower half is purpose-designed to contain the complete control and instrumentation systems, including start-up equipment, a screened bell-mouth air inlet, and kerosene fuel tank and pumps.

A number of modifications has been made to the design of the Rover gas turbine. Certain holes in the turbine inlet volute, originally intended to improve the annular temperature distribution around the turbine inlet nozzle guide vanes, have been blocked, based on our belief that the temperature profile of hot gas from the cyclone combustor should be far more uniform than that presented by the standard Rover kerosene burner configuration (relevant tests conducted on a similar installation at Barnstaple, UK have confirmed this supposition). The benefits are increased mass flow through the pressure circuit and, most importantly, reduced temperatures in the combustor and turbine inlet pipework.

The Rover start-up system has been completely replaced by a more powerful, programmable, drive unit capable of accelerating the alternator to 40% of maximum speed whilst "cold", i.e. without the benefit of chemical energy from fuel. This is necessary due to the large volume and thermal inertia of the biomass gasifier and cyclone combustor. It allows start-up to be achieved more quickly and minimises the duration and magnitude of temperature excursions during the start-up phase. The circuit diagrams for the start-up unit (backdrive and excitation power supply) are shown in Figures 5a & b.

The lubrication system on the Rover has also been changed to allow the oil level to be monitored and replenished during extended periods of operation.

The standard air inlet to the compressor has been replaced with a special bell-mouth that extends downwards into the lower half of the gas turbine console, which is protected from inadvertent ingestion of random debris by metal mesh screens.

The design of the load bank is based on a unit already installed in the JET rig at Barnstaple. Three banks of resistive elements convert up to 40 kWe of electrical power into heat which is then dissipated by a surrounding jacket of water that is continuously replenished. Elements may be switched in and out individually and the electrical load is controlled through the same excitation power supply that is integrated into the alternator backdrive unit. One bank of heating elements doubles as a braking resistor for the backdrive unit.

3.1.1.6. Whole plant control system

Detailed contributions were required from all partners before the whole plant control system design could be finalised, viz.: (i) GT control and safety systems from J.E.T., (ii) gasifier/ combustor control system from dk- TEKNIK, (iii) dynamic model of conceptualised whole plant control system from Numeca.

The gas turbine control system (i) is a development of that supplied with the Rover engine, i.e. three spill valves: two being opened by a centrifugal governor which reduces fuel flow to the kerosene burner at approximately 48000 and 50000rpm, and the third valve opening when the jet pipe temperature exceeds a critical value. J.E.T. has introduced a fourth spill valve for manual adjustment of engine speed, and a series of automatic trips which are activated under anticipated fault conditions. When the set is tripped, the fuel supplies are cut off, the load disconnected and, under special circumstances, the compressor blow-off valve is opened. The blow-off valve applies an additional load to the rotating assembly in the event of a sudden disconnection of the electrical load, thus preventing a serious overspeed. The blow-off load must be capable of rapid application but it should not be allowed to lead to an unacceptable increase in turbine temperature. This is achieved by fitting the valve with an outlet orifice designed to ensure a satisfactory compromise between load magnitude and acceptable temperature rise. Quite clearly, the blow-off valve must only be activated by an overspeed condition; if activated when the jet pipe temperature (JPT) limit is exceeded, the consequences could be severe overheating of the turbine rotating assembly. The trip logic is designed to achieve the above requirements.

The dynamic whole plant model of the Barnstaple rig (supplied by Numeca) has allowed J.E.T. to test the control system design under simulated fault conditions, and has confirmed that the blow-off valve in the compressor outlet should provide adequate protection against faults whilst installed in the main test facility at Risø. Preliminary tests on a similar installation at Barnstaple (UK) have also indicated that an adequate level of protection should be achieved.

As a further safety measure, the bolts in the end cover of the combustor pressure vessel will be spring loaded. This complements the function of the bursting disc in the end cover.

3.1.1.7. Instrumentation and monitoring equipment

The instrumentation and monitoring equipment logs and displays parameters throughout the entire facility. The parameters shown in Table 1 were planned to be logged. Certain parameters that are critical to operator activities would also be displayed as virtual instruments on a PC VDU via an 11 channel A-D converter using PICOSCOPE software. Another PC logs all parameters via a 22 channel A-D converter using PICOLOG software. This arrangement allows certain channels to operate alarms should critical values be exceeded. It can also compute, in real-time, derived parameters such as mass flows, pressure ratios, and efficiencies. Each parameter may be sampled at up to 100 times per second. Each sensor is connected to a central "Instrumentation Box" via individual signal conditioning units. The instrumentation box outputs to the PCs via the A-D converters. The gas turbine/alternator instrumentation system is shown diagrammatically in Figure 6.

A control panel on the lower half of the gas turbine console also displays JPT (digitally) and oil pressure and compressor outlet pressure in analogue form, see circuit diagrams in Figures 7a & b. JPT is measured at four circumferential locations, which can be read from the same digital display; this gives an approximate indication of the temperature distribution around the nozzle inlet guide vane ring. Engine starts, running hours and fuel tank level are also displayed.

3.1.1.8. Design and operational "Manual"

A "Manual" was created in loose-leaf folder format. It comprises the following Sections:

- Description of the facility and design intent
- Start-up cycle procedure (kerosene fuel)
- Introduction of wood fuel
- Procedure for application of electrical load
- Shut-down procedure (normal and emergency)
- Data logging and display equipment and operation
- Control systems
- Alternator backdrive equipment and settings
- Manufacturer's data (handbooks and specifications) for:
  - Rover gas turbine
  - Transducers
  - Valves
  - Sensors
  - Motors
  - Drive units
  - Logging and instrumentation displays

3.1.2. Facility Construction (Task 2)

The facility construction has included the procurement of the pressure vessels and the gasifier/combustor along with necessary piping etc. The delivery of the pressure vessels were postponed due to the Danish strike in spring 1998. This delayed the assembly of the rig at laboratories. The rig was assembled at Risø (Figures 8a & b) in August 1998. The fitting of the turbine to the rig could not be done after the atmospheric experiments had been carried out, this did not happen.

One major outstanding problem was the explosion precautions. dk- TEKNIK were trying to come to terms with AT on this matter before pressurised operation could begin.

3.1.3. Dynamic Model (Task 3)

The development of the dynamic model simulating the 'dual fired' gas turbine has been completed. It is fully described in Deliverable 3/3(10). The arrangement that is modelled is a Rover model 80 gas turbine from which the original combustor has been removed. The main components modelled are the compressor, the combustor, the turbine, the alternator and the speed control system. A PC-based simulator has been developed, that is associated to the model in order to provide an interface with an operator.

A global description of the work performed under Task 3 can be found in Annex A.

The model is operational, with the aid of an associated user interface, it has not been independently verified. Validation of the model will not be possible until sufficient quality data are available. However some confidence in gas turbine aspects of the model is given by the correspondence which has been found between the Barnstaple rig and the earlier version of the model with a steel combustor.

3.1.4. Particulate Flow Modelling (Task 4)

A global description of the work performed under the part of Task 4 devoted to the combustor can be found in Annex B. For particulate flow modelling, simulations of the flow in cyclone chambers have been performed with the Numeca's FINE™ environment, which permitted to customise and validate the Numeca CFD code for this kind of application, and to guide the design of the Biogasifier combustor. The results of the simulations were convincing and are described in Deliverables 4/2a and 4/2b.

A Lagrangian particle tracking algorithm has been implemented in the Numeca solver. The gas-particle interaction model has been validated on basis of various analytical and experimental test cases (Deliverable 4/3).

In the LDA - CFD comparison, for the first deliverable the high accuracy of the velocity field predictions by the Numeca flow solver has been proven through the simulation of a well documented and published cyclone configuration. The Figures B2 & 3 presenting the circumferential velocity component radial distributions at different axial positions clearly show the close correspondence between the modelling results and the measurements provided by dkT.

A simulation of the gas and particles flow in the turbine stage is described in Annex D. The air and particles flows in the gas turbine stage have been simulated with the Numeca CFD tools, the results clearly showing the large influence of particle size. Such simulations are helpful in order to establish the constraints to be set on the size of the particles entering the turbine in order to ensure an acceptable life time. These models for the turbine blading stages have been partially validated by observations of deposits on blades in the directly biomass fired Barnstaple rig, in that very little deposition has been noted, virtually all the ash particles entering the turbine are of sub-micron dimensions.

3.1.5.

3.1.6. Fuel (Task 5)

The change of the fuel auger system called for fuel at certain sizes, i.e. pellets made from wood shavings etc. from wood industry. These pellets were procured and were ready for the atmospheric tests at Risø. No further changes have been introduced to this task.

References for two southern European fuels have been identified and would have been evaluated. For a description of the work carried out in this task, see Annex E.

3.1.7. Facility Commissioning (Task 6)

The commissioning of the plant began on the 5th September 1998. Cold tests of the plant by means of a fan for atmospheric testing were commenced and unveiled leaking spade valves in the lock hopper system. Immediate action was taken to eliminate the leaks as new spade valves were bought. A number of leaks showed after the new spade valves were fitted. All leaks needed to be identified before ignition in the gasifier could take place. At contract termination a minor leak still was not identified.

The leaks were not anticipated to affect the cold LDA tests on the combustion chamber.

3.1.8. Experimental Programme (Task 7)

The experimental programme commenced early in September by cold LDA testing to determine the flow pattern in the cyclone combustor. The results of this are described in Annex C.

3.2. Comparison of Planned and Actual Work Performed

3.2.1. Facility Design (Task 1)

Details of the changes from planned to actual work content are included in the overview description given in Section 2.1.1.

3.2.2. Facility Construction (Task 2)

The gas turbine part of the system was completed to the original schedule.

The Danish strike led to a postponement of the assembly of the gasifier/combustor into the pressure tanks. This should have been done by the end of June. The work was performed around the start of August without any serious delay. The rig was assembled at the end of August ready for atmospheric testing. If commissioning and testing runs had taken place without difficulties the gas turbine would have been installed in the middle of September ready for commissioning by the end of September. This was not achieved.

3.2.3.

3.2.4. Dynamic Modelling (Task 3)

The completion of the development of the model has been provided on time. It has been postponed from Month 6 to Month 10 when compared to the initial list of Deliverables of the Technical Annex, due to the delay on the establishment of the gasifier-combustor design.

The outstanding task was the validation of the model on basis of the experimental data obtained on the plant. This should have taken place after Month 16.

3.2.5. Flow Modelling (Task 4)

The Task 4 was on time. All CFD models required under the framework of the contract are available and have been validated. The gas-particle flow in the turbine has also been simulated, this is described in Annex D. The outstanding tasks were the simulation of the cyclone and the refinement of the models as a result of the comparison with experimental results.

3.2.6. Fuel (Task 5)

Since the fuel auger changed from a screw auger to a reciprocating auger for wood chips it has been necessary to change the first fuel into a pelletised fuel. The fuel constituents remain the same.

3.2.7. Facility Commissioning (Task 6)

The facility commissioning in atmospheric mode was not completed. The gas turbine would have been mounted on the rig for pressurised commissioning would also have been subject to Danish “AT” approval which would not be given until the whole rig was assembled.

3.2.8. Experimental Programme (Task 7)

The experimental programme description has been reported. The only experimental programme which was completed was the cold LDA tests, this is described in Annex C.

3.2.9. Pre-production Prototype (Task 8)

The task is scheduled for the latter part of the project but JET has made a start by visiting a number of potential manufacturing suppliers and customers, including:

Rolls-Royce
Alstom (EGT and Napier)
British Gas
British Energy (SABRE Power)
Polaron-Cortina
ESD
Border Biofuels.

These contacts will help in the formulation of market requirements and the positions of potential competitors, as well as the availability of critical components for incorporation into the prototype.

3.3. Comparison of Achieved and Stated Objectives

3.3.1. Facility Design (Task 1)

The objective of Task 1 was to design of an instrumented test facility comprising: pressurised gasifier, cyclone combustor, control system, gas turbine, alternator, load bank and deposition probes.

The Deliverables that have been achieved are the following:

1/1 (specification): conceptual design and outline specification
1/2a (drawings): balance of plant general assembly sketches complete (initial design)
1/2b (drawings): gasifier/combustor general assembly sketches complete
1/3a (drawings): balance of plant manufacturing drawings complete (initial design)
1/3b (drawings): gasifier/combustor manufacturing drawings complete
1/4 (report): design intent complete.

The next Deliverable would have been due by the end of Month 19.

3.3.2. Facility Construction (Task 2)

The objective of Task 2 was construction of the test facility.

The Deliverables that have been achieved are the following:

2/1a (report): balance of plant procurement complete (initial design)
2/1b (this report): gasifier/combustor procurement complete
2/2 (this report): construction complete and to specification
2/3a (operation): balance of plant components tested.

The next Deliverable would have been due Month 17.

3.3.3. Dynamic Modelling (Task 3)

The objective of Task 3 was to develop the full dynamic model, which has been provided. The second year would have permitted confirmation of the validity of the model.

The Deliverables that have been achieved are the following:

3/1 (specification): selection of the software
3/2 (report): intermediate report
3/3 (report): final description of the model.

The next Deliverable (due by the end of Month 23) should have been based on the comparison between the model results and the measurements.

3.3.4.

3.3.5. Flow Modelling (Task 4)

The Task 4 was on time. All CFD models required under the framework of the contract are available, and have been validated. More calculations have been performed than planned, in order to guide the design of the combustor. The calculation of the flow in the turbine stage including the simulation of the particles has been performed (Annex D).

The Deliverables that have been achieved are the following:

4/1 (specification): selection of the CFD models
4/2a (report): description of the cyclone (non reacting) flow simulations
4/2b (report): description of the cyclone (reacting) flow simulations
4/3 (report) : description of the Lagrangian gas-particle interaction model

The results of the turbine flow simulations are not included in these deliverables. They are briefly presented in Annex D.

The next Deliverable (due by the end of Month 24) should have concerned the results of the cyclone & turbine simulations, with comparison with the measurements..

3.3.6. Fuel (Task 5)

The objective of Task 5 was preparation and analyses of a range of suitable fuels.

The Deliverables that have been achieved are the following:

5/1 (specification): 4 biomass fuels with options identified
5/2 (supply): start supply of fuels with reference "clean" fuel.

The next Deliverable would have been due by the end of Month 21.

3.3.7. Facility Commissioning (Task 6)

The objective of Task 6 was to achieve facility commissioning.

The deliverable would have been due by the end of Month 19.

3.3.8. Experimental Programme (Task 7)

The objective of Task 7 was to plan, measure, analyse and report performance, deposition, corrosion and erosion parameters.

The Deliverables that have been achieved are the following:

7/1 (programme): outline experimental programme /deliverable list prepared
7/2 (programme): detailed experimental programme /deliverable list prepared

The next Deliverable would have been due by the end of Month 21.

4. CONFERENCE PRESENTATIONS

The partners attended the Kenilworth "Wood Fuel at Work" conference in October 1997, J.E.T. contributed to the Poster Session with a display which included reference to this project.

The partners produced a brochure covering the work of this project for the "Biomass for Energy and Industry" held at Wurzburg in June 1998 (Ref.9). A Poster presentation was proposed and prepared in good time, but was not included due to an error by the conference organisers.

5. PROJECT PROGRAMME REVIEW

5.1. Summary of Progress

5.1.1. What Has Been Achieved

The detailed work is described elsewhere in this report, the following is a summary of what has been achieved.

a) The overall system design was developed, overcoming a number of potential control problems.

b) A dynamic system model was developed and partially validated (on a GT direct combustion facility). This was utilised to assist in overall system design.

c) The gas turbine system complete with its instrumentation and control systems were designed, assembled and as fully commissioned (in isolation) as is possible; in reaching this stage, a number of significant technical problems were overcome.

d) The pressurised gasifier and combustor systems were designed and manufactured, leakage and atmospheric pressure testing were started.

e) A novel approach to the interconnecting pipework (which has high temperature components) was developed, the pipework manufactured and assembled ready for installation between the GT and the gasifier / combustor.

f) Flow models of the combustor which could incorporate particulate and reactive components were developed and used to support combustor design. Preliminary modelling of the GT flows was also started.

5.1.2.

5.1.3. Potential Unsolved Problems

Prior to the decision to recommend abandonment of the project, the following potential unsolved problems had been recognised:

a) Failure to start

The combined volume of the gasifier, combustor and interconnecting pipework is very much larger (x100) than the standard Rover combustor. Heat transfer between the kerosene flame and the large thermal mass of steel and refractory results in extended start-up times and, more importantly, high transient temperatures during start-up. The calculations involved many assumptions and estimates but there remained a risk that start-ups would have to be aborted. The present design partially solves this anticipated problem by supplementing the liquid fuel (kerosene) energy by electrical energy from the starter motor (backdrive) system. A more powerful and much more expensive backdrive unit could have been purchased but that would have meant that costs would have needed to be cut elsewhere; the size of the backdrive unit was limited to a practical maximum of 15 kWe. It was reasoned that a potential “fall-back” could be to provide some preheat before attempting a start-up. This would be time-consuming and involve some expenditure, but much less than a larger backdrive.

The underlying reasons for the large size of the system are explained in Section 3.1.1.2.

b) Debris ingestion

Ingestion of virtually any kind of debris, refractory or metallic, would cause serious damage to the turbine, and possible curtailment of the project. No collection efficiency data are available for the debris retention system that is built into the cyclone combustor exit pipework, so the actual risk could not be assessed. J.E.T. had no financial provision to replace a damaged turbine.

c) Turbine case distortion

Thermal and system loads imposed upon the turbine case by the massive gasifier/combustor/pipe assembly must be controlled effectively, otherwise the relatively delicate turbine case will distort, leading to interference between rotating and stationary parts, and possible severe structural damage. The normal solution to such problems is to use flexible bellows units to accommodate the induced strains, but the present design depends upon the pipework being anchored to the sliding turbine console framework.

d) Control system inadequacies

Although the dynamic model of the facility suggests that the proposed control and safety systems should function satisfactorily, the model had not been validated. The thermal inertia of the gas circuit is very much larger than the rotating inertia of the gas turbine rotor, thus placing severe demands on any control and safe shutdown system. If turbine inlet temperature and rotor rpm could not be held within safe limits, the plant could not be declared safe to operate.

f) AT Approval

AT (the Danish safety authority) had to inspect the plant before operation at full temperature and pressure could commence. If they had insisted upon extensive modifications, this would have added significantly to the cost of the project.

g) Combustion Ignition

There has through the project been much thought on how to ignite the gasses from the gasifier. In atmospheric “Two-Stage Combustion” (TSC) the problem is non existent as it is possible to run an oil burner for ignition purposes. Under pressurised conditions this is not possible. The start up procedure has consisted of a phase of over-stoichiometric operation at higher temperatures in the gasifier, in order to heat up the cyclone combustor, followed by a phase with a cutback of air in the gasifier and ignition by glow heads of the resulting producer gas entering the preheated cyclonic combustion chamber. This is an unproven situation.

h) Modelling Tasks

Concerning the modelling tasks, the dynamic model for the plant simulation as well as the CFD models for the prediction of particle deposition have been developed and validated on basis of various testcases (the Barnstaple combustor for the dynamic model, various generic and industrial testcases for the CFD models); the opportunity of validation of both models on a new complex configuration would have been of great interest in order to establish a confidence on their accuracy for the analysis and design of particular gas-turbine systems such as the one developed under the contract.

i) Unanticipated problems

All of the problems listed above had been anticipated during the design phase, and provision made to minimise their impact. The success of these provisions would not be known until commissioning was complete. As with any RTD project, however, there may also be unanticipated problems that could have serious consequences for the project.

5.1.4. What Has Not Been Achieved

The following is a summary of what has not been achieved.

a) Atmospheric and pressurised operation of the gasifier / combustor.

b) AT commissioning approval of the overall system.

c) The facility operated and commissioned at pressure with the gas turbine.

d) The planned experimental programme.

e) Validated overall dynamic model of the system with testing of the control and protection arrangements.

f) Comparison of the results of the turbine flow simulation with the experimental results.

g) Modelling of the particulate and possibly reacting flow models for the combustion system, and comparison between the numerical and experimental results

h) Refinement of the CFD models on basis of the comparison with the measurements, and establishment of a validated particulate and flow model for the design and development of robust GT's.

i) Exploitation plans for each of the partners and for the overall system and concept.

5.2. Reasons for Failing to Achieve the Planned Objectives.

It was recognised that the overall programme had fallen considerably behind schedule after seven months, this led to the need to seek agreement from the Commission for a revision to the timetable (but not to the important objectives). Due to delays in the design of the gasifier / combustor system as it needed redesign, it was not possible to meet the original schedule of starting commissioning of the combined system in January 1998. These delays essentially led to the overall programme being about seven months behind schedule. The recovery plan intended to catch up on the delays. However a Danish major strike delayed component delivery. Assembly of the rig was consequently delayed for 1.5 month.

Included in the contributory difficulties was the need to obtain approval from the Danish regulatory authorities (AT) for the design and construction of the 16 bar pressure containment of the gasifier and combustor. There were also a number of detailed design problems to be overcome, including the potential endurance and efficiency problems if high temperature control (as opposed to protection) valves needed to be incorporated.

While all of the recognised problems were overcome, all potential difficulties in the gasifier / combustor could not be foreseen in detail, this led to it being unrealistic to achieve commissioning followed by the experimental programme within the contractually agreed timetable. A realistic view is that a further six months would have been required, in addition certain of the important costs were substantially above budget, particularly with dk-TEKNIK for the gasifier / combustor development and for J.E.T. for additional project management and design / manufacture costs which arose because of the early delays.

5.3. Consequences of Failing to Achieve the Objectives

The underlying objectives for the project relate to the incorporation of robust low cost gas turbines with a pressurised biomass gasifier / combustor system for CHP. In the period since this project was proposed, the potential cost of a commercial gas turbine / generator system (but not yet developed) should be significantly less than originally suggested; this will be of importance in making the technology available at acceptable cost and efficiency. The economic arguments in favour of this project for achieving gasifier based biomass CHP are if anything stronger than when the project was proposed. No fundamental reasons for failing to achieve the main objectives have been identified, the potential for exploitation has been seriously delayed.

The CFD models have been validated on basis of various testcases. However the comparison with the measurements that was planned under the framework of this contract would have permitted to establish their validity for this particular kind of application. This is essential in order to prove their applicability for the design of both combustors and the hot stages of robust, biomass fired gas turbines, which can cope with reduced quality gas flows. These tools, together with dynamic modelling tools continue to be required to provide a sound basis for future designs.

5.4. Options Available to Take Advantage of the Progress Made

Essentially all of the hardware for this project, together with many of the basic modelling tools now exist. There is reason to believe (while recognising the potential problems listed in Section 5.1.2) that there are no problems which cannot be solved during a well planned and managed engineering and scientific development programme. Once operating, the facility will be available, not only for the programme which was proposed for this project, but also for providing information for other Commission projects. It is worth recognising that it is very difficult to “reproduce” many of the important characteristics (e.g. high temperature, very high velocity, realistic gas / particulate flows at pressure) without using a gas turbine. This type of facility is also essential to validate the combustion, GT flow and control models which are required.

The partners would therefore welcome the opportunity to discuss with the Commission the options available, either in isolation or possibly linked to other Commission projects, to realise the potential of the investment by both the partners and the Commission in the hardware and modelling tools which now exist. It should be recognised that the major hardware costs have already been committed.

The following more specific benefits have been attained.

It is likely that any future successful project should be based on and possibly managed around the development of the gasifier / combustor system. While dk-TEKNIK has learned very little from the project, as it ended before results from hot tests were available, it seems as though the proposed design is still promising and dk-TEKNIK will try to set up the rig in atmospheric mode. This will be a subsequent Danish project and will involve the former subcontractor DanTrim as this is the only way to pursue the whole idea. To take the development further, DanTrim will have to invest money themselves from now on. Results from these atmospheric tests will support a future proposal to the commission or others that might have an interest in the development.

Certain of the features of the J.E.T. rig which was built within this project, were developed here (aspects of the liquid fuel feed, control and safety systems). These features are incorporated in a separate direct biomass combustion fired gas turbine facility (funded otherwise by J.E.T. and the UK Government) which has potential to generate financial income both as a facility and through offering similar rigs for hire or sale as research facilities.

The dynamic model which was developed in close collaboration between Numeca, J.E.T. and dk-TEKNIK adapted an existing model validated on the direct combustion Barnstaple Rig to the new configuration including a gasifier and a cyclonic chamber. The model is operational, with the aid of an associated user interface.

For CFD developers such a project offers the unique possibility to have a deep validation of the models, including a detailed comparison between the numerical and experimental results. The work which has been done goes some way towards this objective.

For combustor related particulate flow modelling, the CFD tools developed by Numeca have been used to simulate the flow in the GT-Biogasifier cyclonic chamber, with validation on published experimental test cases, further validation has been obtained from the cold LDA tests.

In the gas turbine flow and particles simulation, the air and particle flows in the gas turbine stage have been simulated with the Numeca CFD tools, the results clearly showing the large influence of particle size. Such simulations are helpful in order to establish the constraints to be set on the size of the particles entering the turbine in order to ensure an acceptable life time. This has been partially validated by observations of deposits on blades in the Barnstaple rig, in that very little deposition has been noted, with virtually all the ash particles entering the turbine are of sub-micron dimensions.

6.

7. REFERENCES

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TABLE 1: PROPOSED MEASUREMENT SCHEDULE

TABLE 1: (CONT.)

FIGURE 1: PLANT LAYOUT

FIGURE 2: GASIFIER, COMBUSTOR AND PRESSURE CIRCUIT

FIGURE 2 (cont.): GASIFIER, COMBUSTOR AND PRESSURE CIRCUIT

FIGURE 3: CONNECTION BETWEEN GAS TURBINE AND PRESSURE CIRCUIT

FIGURE 4: GAS TURBINE SYSTEM

FIGURE 5: GT/ALTERNATOR EXCITATION PS AND BACKDRIVE SYSTEM

FIGURE 6: GT INSTRUMENTATION LAYOUT

FIGURE 7: GT AND TEST STAND CONNECTIONS

FIGURE 8: GASIFIER AND COMBUSTOR AT RISØ

ANNEX A: DYNAMIC MODELLING

Task 3 - Dynamic modelling of the plant and control system

1. Summary

The work accomplished during the first year of the contract was the development of the dynamic model.

The system that is modelled is dual fired gas turbine. The main components modelled are the compressor, the turbine, the alternator and the speed control system. The combustor consists of a cyclone combustor and a kerosene burner. Equations are included to allow full dynamic simulation including: the rotational speed, combustor pressure and combustor components temperature. A generic controller for the turbine speed is included which has proportional and integral actions. This is modelled on the Rover controller and acts only on the kerosene flow. The compressor and turbine characteristics are taken to be the same as in the steady state.

A first intermediate model has been developed, which had a different combustion system as the one constructed under the framework of the contract. This combustor had a steel arrangement, which allowed kerosene and wood to be burned in the same combustion chamber. The current arrangement uses a refractory lined pressurised gasifier into which the biofuel is fed and converted into a gaseous fuel, which is burned in a cyclone burner. The gas from the cyclone burner is fed to the turbine. In addition a kerosene burner operates in parallel.

The model uses the VisSim simulation code. This allows variables to be displayed and for the user to change parameters during the simulation. VisSim has a viewer facility, which allows the user to run a simulation without access to the full code. The user can change all modelling parameters, but the model structure cannot be altered.

2. Model overview

The arrangement that is modelled is shown schematically in Figure A1. It comprises a Rover model 80 gas turbine from which the original combustor has been removed. The turbine drives an alternator via a reduction gearbox. The output from the alternator is dissipated in a resistor bank.

The compressor supplies air to: the kerosene burner, the gasifier and the cyclone burner. The air flows are controlled by the primary air control valve, the secondary air control valve and the kerosene burner valve respectively. These valves are adjusted manually.

Fuel is supplied to the gasifier by means of a moving grate. The air is controlled so that the biofuel is converted into a combustible gas (producer gas) rather than being completely burnt. A proportion of the calorific value of the fuel is released. The gas from the gasifier passes to the cyclone burner, where additional secondary air is added and combustion of the producer gas takes place.

The kerosene burner is placed in parallel with the bio-burner although the gas from the kerosene burner is mixed in the cyclone before passing to the turbine. The gasifier and the cyclone have refractory linings and each has a significant enclosed volume. Thus the effects of heat transfer from the gas to the refractory have been taken into account. The compressibility of the gas in the gasifier and the cyclone has also been modelled.

The structure of the model is shown schematically in Figures A2 & A3. Figure A2 shows the overall model structure and Figure A3 shows the structure of the gasifier. The main sub-modules are the followings:

- compressor: calculated the temperature rise of the compressor given the inlet pressure and temperature and the outlet pressure
- burners: calculated the pressure and temperature of the gas flow to the turbine and ensures that the pressure and mass flow from the compressor conform to the compressor characteristics
- turbine: takes the input pressure and temperature and calculates mass flow from the characteristics and power output.
- rotational speed: calculates the shaft speed from the net power supplied to the shaft.
- alternator
- speed control: acts to maintain speed, at the value selected by the slider control, by altering the kerosene fuel flow.
- emergency trip button: simulates a turbine trip and causes both fuel supplies to be reduced to zero.
- heat transfer turbine inlet to compressor outlet

2. VisSim modelling

A VisSim model consists of a series of blocks linked together. Each block performs a simple function such as add, multiply, constant integration, etc. By combining a number of blocks together equations can be represented. VisSim provides the means to solve the equations and to integrate differential equations with time to calculate the transient response.

Whilst the individual blocks may be displayed, with a large model it would be impossible to understand the model. To facilitate better understanding of the model structure it is possible to combine a number of blocks together as a single compound block. This can be done at any number of level thus creating a hierarchical structure. The model is partially self documenting, the user guide therefore provides a map to the structure and content of the model.

VisSim runs under the Microsoft Windows operating system and the current model has been developed under Windows 95.

3. Short description of the use of the model

The model structure has been set and cannot be changed by the user. However the user can alter the values of any of the numerical variables within the model. Facilities are included for easily changing the load profile and the set up of the valves which control the distribution of the air to the combustor.

The compressor and turbine characteristics are defined as tables, which are input to the model by means of maps. The maps are held in separate text files, which the model must be able to access.

Various integration methods are available as VisSim options and may be selected by the user. This also allows the length of the simulation and the time step to be changed.

4. Validation of the model

The model has not been independently verified. Validation of the model will not be possible until sufficient quality data are available. However some confidence in the model is given by the correspondence which has been found between the Barnstaple rig and the earlier version of the model with the steel combustor.

FIGURE A1: GENERAL ARRANGEMENT OF BIO-FUELLED GAS TURBINE

FIGURE A2: SCHEMATIC OF MAIN MODEL MODULES

FIGURE A3: GASIFIER MODULE

ANNEX B: COMBUSTOR PARTICULATE FLOW MODELLING

Task 4 - Particulate flow modelling

Summary

The work accomplished during the first year of the contract can be decomposed in 2 parts:

- the simulation of the cyclonic combustion chamber, with the objectives of customising the Numeca flow solver for this particular flow configuration, and guiding the design of the cyclone chamber constructed under the framework of the contract. The results are summarised in Deliverables 4/2a & 4/2b.
- the implementation of a Lagrangian gas-particle interaction model in the Numeca flow solver. The description of the model and of its implementation are described in Deliverable 4/3. The model has been validated on basis of analytical and experimental test cases.

1. Simulation of the cyclone chamber

Validation of the Numeca flow solver for the cyclone flow prediction

A validation test case has firstly been performed, analysing a cyclone geometry for which detailed experimental and numerical data are available in the literature. This first geometry is similar to the one proposed to dk-TEKNIK, although it only comprises 2 pairs of injectors, through which identical fluids are blown (at the same temperature).

This validation step permitted to establish the accuracy with which the Numeca FINE^{TM}/Turbo solver is able to predict the flow in cyclone chambers.

In the present work both axisymmetric and 3D computations have been considered. Basically the flow field inside cyclone chambers is three-dimensional, and the complexity of the flow field requires a fine discretization in axial and radial directions. However, the results obtained show that the flow gradients in the circumferential direction are very strong only in some regions, i.e. in the vicinity of the injectors. Axisymmetric flow simulations can therefore lead to reasonable predictions of the most important features of the flow. This simplification allows for a significant reduction in calculation time and storage requirement.

The multi-block structured mesh generated inside the geometry using the Numeca IGG^{TM} interactive grid generator is shown in Figure B1. The circumferentially-averaged streamlines projected onto the (y,z) plane (Figure B2) permit to observe the complexity of the flow field. Quantitative comparisons between the measured and calculated circumferential velocity components are presented in Figure B3. Also shown is the distribution of the axial component of the velocity, which is compared to the measurements along several radial lines. These comparisons permit to verify the accuracy with which the flow field is predicted by the solver, and also confirm the axisymmetric character of the flow.

Simulation of the GT-Biogasifier cyclone geometry

The dkT geometry has then been analysed, which comprises 5 pairs of injectors (one of them being the fuel inlet). Several modifications of this design have been proposed and tested, which permitted to confirm the validity of the design proposed by dk-TEKNIK.

Preliminary calculations have been performed assuming a single perfect gas in the chamber, having the same characteristics as the air. These purely aerodynamic simulations of the GT-Biogasifier geometry revealed a satisfactory flow field in the design proposed by dk-TEKNIK, as residence time of the fuel is concerned. Figure B4 shows the streamlines projected onto the (y,z) plane. The trajectory of the fuel (in red) can be distinguished from the air.

Several modifications of the design have been proposed and tested, such as a shorter design or a lower number of air injectors. These modifications led to a shorter trajectory of the fuel particles, and hence to a probably lower efficiency of the combustion.

These preliminary calculations did not account for the reality of the gas entering the chamber through the fuel injector, and also neglected the effect of chemical reactions, and in particular the high energy release created by the fuel combustion. Additional calculations have been performed, considering the effects of the reality of the fuel and of the chemical reactions on the flow. No hypothesis has been made on the fuel composition. The only chemical reaction that has been introduced in these preliminary calculations is the combustion of the methane. The calculated streamlines are shown in Figure B5, and show that the main flow characteristics are not different from the ones predicted by the single air calculations. Figure B6 shows the calculated static temperature in the chamber, which show the effect of the combustion, leading to an exit temperature of the order of 1100 K.

2. Integration of a Lagrangian particle tracking algorithm into the Numeca flow solver

The main objectives of the Project from the CFD point of view is to have the opportunity to simulate a complex solid-gas flow interaction problem, and to refine the models in interaction with the measurements.

The Lagrangian approach has been selected for the modelling of the gas-particle interaction. In a Lagrangian model, the motion of the particles is only influenced by their own inertia and by the flow, i.e. the local aerodynamic forces. There is no interaction between the particles. This implies the hypothesis of a 'dilute' flow. On the contrary in a 'dense' flow, particles motion is governed by their direct interaction, which implies more complex models, such as the Eulerian ones, in which both phases are modelled with an Eulerian treatment.

The calculations of the carrier flow and of the particles can be fully (2-way) or weakly (1-way) coupled:

- the 1-way coupling approach means that the classical flow calculation is followed by a calculation of the particles trajectories. There is no influence of the particles on the flow.
- the 2-way coupling approach means that the particles trajectories calculation will be followed by a second flow calculation, taking into account the presence of the particles in the flow (the interphase forces are introduced as source terms in the flow calculation). The

sequence can be repeated several times until no changes are observed (usually 5 to 10 times).

The calculation of the trajectories is based on the Newton law, whereas the interphase force vector is calculated according to the Stokes law. There is for the moment no model in which the mass and the volume of the particle would change, for instance by combustion or evaporation.

Emphasis has been put on the influence of the turbulence of the carrier phase on the particles motion. A stochastic treatment has been adopted, which involves the direct simulation of the particles behaviour in a random flow field. Using of the k-ε turbulence model is assumed for the carrier flow simulation.

The validation case presented here is a two-phase planar mixing layer with polydispersed drops, for which detailed experimental data are found in the literature. A vertical wind tunnel was divided into two separate flow paths by a central splitting plate. The mean velocities of the high- and low-speed streams were equal to 10 and 2.3 m/s respectively. The high-speed stream was seeded by polydispersed water drops whose diameters ranged from 3 to 100 mm. Measurements of the carrier and particle flow velocities have been performed at several streamwise positions.

The computational grid used in this test is shown in Figure B1, which also represents the carrier flow velocity field. The calculations have been made with a 2-way coupling between the two phases. Four full cycles have been performed, each of them consisting a flow calculation followed by the particles tracking.

Different types of particles (in terms of size and velocity) have been introduced, the total number of probe particles being 19200 (20 particles per inlet cell, for each particle type). The comparison between the calculated and measured carrier flow velocity fields are shown in Figures B3 & B4. One can observe that the streamwise velocity component is very well predicted, whereas the transversal component is underestimated at the exit. The comparison between the calculated and measured particles flow fields is shown in Figures B5 & B6, which permit to draw the same conclusions. One can notice that the transversal velocity component is better predicted for the particles than for the carrier flow.

FIGURE B1: VALIDATION TEST CASE – 3D VIEW OF THE MESH

FIGURE B2: VALIDATION CASE – VELOCITY DISTRIBUTION IN CENTRIFUGAL PLANE OF 2ND INJECTOR, CIRCUMFERENTIAL VELOCITY DISTRIBUTION

FIGURE B3: VALIDATION CASE – VELOCITY DISTRIBUTION IN CENTRIFUGAL PLANE OF 2ND INJECTOR, AXIAL VELOCITY DISTRIBUTION

Axisymmetric simulation – 1 single perfect gas

FIGURE B4: CYCLONE CHAMBER – SINGLE AIR CALCULATION

Axisymmetric simulation – 7 species with combustion of methane

FIGURE B5: CYCLONE CHAMBER - REACTIVE CALCULATION

Axisymmetric simulation – 7 species with combustion of methane

T air inlet: 433K, T fuel inlet: 868K

FIGURE B6: CYCLONE CHAMBER – STATIC TEMPERATURE DISTRIBUTION

FIGURES B7 & 8

FIGURES B9 & 10

FIGURES B11 & 12

ANNEX C: COLD LDA RESULTS AND COMPARISON WITH CFD

1. Description of the measurements

The LDA measurements were carried out through 4 quartz glass covered ports in the cyclonic combustor. With reference from the top of the combustion chamber they were placed 230, 560, 910 and 1360 mm away.

The airflow of 0.3 kg/s to the combustor was controlled through valve V6 based on a pitot tube reading. A minor flow was also established and controlled by valve $V4_{by\text{-}pass}$ to simulate a producer gas flow. The latter flow was not measured as that was impossible.

The measurements were carried out with means of RISØ's LDA equipment and staff. RISØ has through the years gained considerable experience into LDA measurements*. The results of the measurements are given in Figures C1 and C2.

2. Comparison with CFD

This section presents the comparison between the LDA velocity measurements and the numerical predictions provided by Numeca.

2.1. Description of the numerical model

The flow simulations have been performed with the Numeca FINE™/Turbo code for internal turbulent flows, solving the three-dimensional Reynolds-averaged Navier-Stokes equations on multi-block structured grids. More details on the mesh (generated with the Numeca IGG™ software) and on the flow solver can be found in Deliverable 4/2.

The flow model that has been considered in this validation phase is **axisymmetric**. A validation case has been presented in Deliverable 4/2a, showing the validity of the axisymmetric model for this type of configuration and the high accuracy with which the FINE™/Turbo solver predicts the velocity fields in cyclonic chambers. The configuration of the flow solver that has been adopted was exactly the same as for the validation case, in order to guarantee the same accuracy on the velocity predictions.

The boundary conditions that have been used are the following:

- Air inlets
  - Total mass flow through the 4 injectors : 0.3 kg/s
  - Static temperature : 433 K

- Fuel inlet
  - Mass flow : 0.075 kg/s

* P.A. Jensen, P.R. Ereaut, S. Clausen and O. Rathmann.: Local Measurements of Velocity, Temperature and Gas Composition in a Pulverized-coal Flame. Journal of the Institute of Energy. March 1994, 67, pp 37-46.

- Static temperature : 868 K

- Exit pressure : 3 bar

2.2 LDA-CFD comparison

Global views of the flow and of the pressure distribution in the chamber are presented in Figure C3, showing the complexity of the flow structure.

Quantitative LDA-CFD comparisons on the tangential and axial velocity component distributions are provided by Figures C1, 2, 4 & 5. The computational results are presented in Figures C4 & 5, showing the circumferential and axial velocity components distributions along 4 radial sections at respectively Z=230, 560, 910 and 1360 mm. These figures can be directly compared to the Figures C1 & 2 showing the LDA corresponding results along the same radial sections.

Tangential velocities (Figures C1 & C4)

A quite close correspondence is observed between the LDA and CFD results. The same type of velocity profile is obtained at the different axial locations, i.e. a profile with zero values at the axis and on the external walls, and with a region of maximum tangential velocity, the value of this maximum velocity being of the order of 35 m/s. Although the LDA results can not be provided in the region located close to the external walls, one can notice a difference between LDA and CFD, which is that in the CFD results the region where the velocity is maximum extends over a wider range.

Axial velocities (Figures C2 & C5)

The complex structure of the flow induces strong variations of the radial distributions of axial velocity along the cyclone axis. One can notice an acceptable global LDA-CFD correspondence on the velocity profiles and on the velocity levels. The detailed comparison of all the profiles permits however to notice some differences:

- Z=230 mm: one can notice that both calculated and measured fields present negative velocities close to the axis and a region of high positive axial velocity (5 m/s) between the axis and the external wall. The position of the maximum is however different between LDA (80 mm) and CFD (115mm).

- Z=560 mm: one can also notice regions of negative and positive axial velocities. The measured and calculated positions of the maximum positive axial velocity differ.

- Z=910 mm: LDA and CFD predictions are similar to the Z=560mm section.

- Z=1360 mm: one can notice a correspondence between the CFD results and the left part of the LDA measurements (negativeY-positions).

2.3 Conclusions

An acceptable correspondence has been obtained between LDA and CFD.

The LDA results clearly show that the three-dimensional effects have a larger influence on the axial velocity field. A 3D numerical model would therefore certainly improve the comparison. This has already been proven through the validation case presented in Deliverable 4/2a, where a much closer correspondence on the axial velocity field has been obtained with the 3D simulations than with the axisymmetric ones.

FIGURE C1: MEASURED TANGENTIAL VELOCITIES

FIGURE C2: MEASURED AXIAL VELOCITIES

FIGURE C3: GLOBAL VIEWS OF FLOW AND PRESSURE DISTRIBUTION

FIGURE C4: COMPUTED TANGENTIAL VELOCITIES ALONG RADIAL SECTIONS

FIGURE C5: COMPUTED AXIAL VELOCITIES ALONG RADIAL SECTIONS

ANNEX D: SIMULATION OF FLUID AND PARTICLE TURBINE FLOW

Task 4 - Particulate flow modelling

The present report briefly describes the results of the application of the Numeca flow solver to the turbine stage of the Biogasifier contract.

1. Input geometry – Mesh generation

The geometry of the rotor and stator turbine blades has been provided by J.E.T., through a series of IGES files. These inputs have been treated with the Numeca's IGG^{TM}/Autogrid software for the automatic meshing of turbomachinery components.

The results of the mesh generation process can be observed on Figures D1 & 2 which show respectively a 3D view of the rotor blades and a meridional view of the whole stage. A leakage gap between the rotor blades and the shroud has been simulated. This permits to simulate the real configuration in which the shroud endwall is fixed.

2. Three-dimensional flow calculation in the turbine stage

The three-dimensional turbulent flow in the turbine stage has been simulated with the Euranus solver included in the Numeca's FINE^{TM}/Turbo user environment for internal flows.

The main characteristics of the flow solver have been presented in Deliverable 4/1. A steady calculation has been performed, which implies that a steady flow configuration is assumed at the rotor/stator interface. Provided that the flow is oriented from the stator to the rotor (which was the case here), one can consider the rotor and the stator calculations as two coupled steady simulations, in which the exit (inlet) boundary condition of the stator (rotor) results from an averaging of the inlet rotor (outlet stator) conditions.

The calculations have been performed with the following boundary conditions:

- inlet absolute total pressure: 3 bar
- inlet absolute total temperature: 1273 K
- mass flow: 0,3 kg/s

A rapid convergence has been obtained for this calculation, whose results in terms of static pressure distribution are shown in Figure D2.

3. Simulation of the gas-particle interaction process in the turbine stage

Having obtained a flow solution in the stage, the Lagrangian model included in the same FINE^{TM}/Turbo environment has been used to calculate the trajectory of wood particles. At the inlet of the stage the velocity of the particles have been assumed to be identical to the fluid velocity. The wall/particle interaction model that has been used is a semi-reflection model, in which the particles remains partially stuck on the wall, whereas the other part is reflected. No incidence effect is included in the model, which should be interesting to incorporate in the future.

Two calculations have been performed, with particles of respectively 1 and 10 microns diameter. The results of these simulations prove the particular importance of the size of the particles. The particle traces are presented in Figures D3 to D6 (the velocity vectors correspond to the fluid velocity field, whereas the continuous lines are the particles trajectories). One can observe that the small particles of 1 micron follow the same trajectory as the fluid (Figures D3&4), whereas the higher inertia of the 10 microns particles induces a high deviation from the fluid trajectory. The heavy particles directly impinge in the turbine walls, as shown in Figures D5&6.

The trajectories depend on the size of the particles and also on their density. It is clear that particles with a higher density than wood would require a more severe limit on their size in order to avoid a too severe fooling of the blades.

4. Conclusions

The predictions of the particles trajectories confirm the importance of a limitation of the size of the particles entering the turbine stages. One of the objectives of the contract was to limit the size to 5 microns. The simulations show that this limit should certainly not be exceeded in order to ensure an acceptable lifetime for the turbine blades.

FIGURE D1: ROTOR BLADES - 3D VIEW OF MESH

FIGURE D2: TURBINE STAGE - MESH & FLOW RESULTS, MERIDIONAL PLANE

FIGURE D3: PARTICLE TRACES IN STATOR - 1 MICRON PARTICLES

FIGURE D4: PARTICLE TRACES IN STATOR - 10 MICRON PARTICLES

FIGURE D5: PARTICLE TRACES IN ROTOR - 1 MICRON PARTICLES

FIGURE D6: PARTICLE TRACES IN ROTOR - 10 MICRON PARTICLES

ANNEX E: DK-TEKNIK TASKS

dk-TEKNIK performed a number of tasks which will be dealt with under the following items:

1. Facility Design and Construction: Task 1 and 2
2. Facility Commissioning: Task 6
3. Establishment of Measurement Programme: Task 7
4. Fuel specifications: Task 5

1. FACILITY DESIGN AND CONSTRUCTION: TASK 1 AND 2

dk-TEKNIK studied different combustor models and designed a combustion chamber that should be able of producing a very clean flue gas for expansion in a gas turbine without the use of expensive Hot Gas Filters (HGF). This input was later used in the Numeca modelling and validated for use in the test rig. Subsequently the combustor design was adapted and constructed.

It is worth to take notice of the size of the cyclonic combustor It is around a 100 times larger than the standard kerosene combustor that normally runs the turbine and it has a thermal mass that exceeds this number many times. The reason for this is to ensure:

- Proper retention time to secure burn out of heavy tars and carbon particles carried over from the gasifier
- Ceramic lining to maintain stable temperature
- Particulate retention due to an advanced cyclonic CFD modelled design that acts as a dust collecting cyclone thus avoiding complex and expensive HGF's featuring high operational costs.

dk-TEKNIK performed a rather large task in the design and construction of the test rig. A number of detailed developments on the interface between the gas turbine system and the gasifier / combustor needed to be carried out during the design process. These included recognition that it would not be possible to utilise a high temperature relief valve as a controllable bypass valve and the re-location of the kerosene combustor from its position at the turbine to the top of the cyclone combustor.

The occupational and health authorities (AT) in Denmark would not allow for the hot pipe materials being exposed to more than 100 mbar pressure difference, necessitating the redesign of the turbine entry pipework to a co-axial arrangement.

The new design was drawn up in an AUTOCAD design package. Some of the drawings are shown in the main report Figure 2 and 3. The design of an integrated loop for the kerosene burner turned out to be another major task as the first design involving a debris trap was rejected due to high heat capacity and subsequent long start-up times or even malfunctions.

Meanwhile dk-TEKNIK had a prime responsibility in developing the "Design and Operating Manual" as this was also a vital document to produce to the AT before an operational permit could be granted. The manual also resulted in minor design changes.

dk-TEKNIK supervised the construction of the plant - both at the subcontractors works and at the final destination at RISØ.

2. FACILITY COMMISSIONING: TASK 6

dk-TEKNIK led the atmospheric commissioning of the rig at RISØ laboratories. The commissioning revealed leak valves in the lock hopper systems. They were replaced.

Afterwards some leaks were still present. As it took a very long time to identify them, and as it could be hazardous to commission the gasifier before they were identified, the gasifier never went into "hot" operation.

During commissioning cold Laser Doppler Anemometry (LDA) flow test were performed. The measurements are discussed in Annex C.

3. ESTABLISHMENT OF MEASUREMENT PROGRAMME: TASK 7

The development of the measurement plan shown in the main report Table 1 was also executed at dk-TEKNIK as well as the design and installation of the belonging measurement ports.

4. FUEL SPECIFICATION, PREPARATION AND SUPPLY: TASK 5

Introduction

In order to test the flexibility of the plant a range of four well-defined wood feed stocks will be made available. The variety will reflect the potential wood fuels in Europe with respect to limitations due to chemical/physical properties.

The major obstacle for running a gas turbine on flue gas from biomass combustion is the alkali content (potassium and sodium), but sulphur and chloride has influence as well. The alkalis can either stay in the ash, condensate on fly ash particles or on other surfaces or form aerosols by homogeneous nucleation. The alkalis forms aerosols with sulphur and chloride (KCl and K_2SO_4 are the most common) which sticks to surfaces and lower the efficiency of the gas turbine be fouling the rotor blades. When potassium (and sodium) is sub-stoichiometric, i.e. moles K+Na/(moles Cl + 2*moles S) < 1, the excess S and Cl is released to the gas as HCl and SO_2. If the alkalis are super-stoichiometric they can form KOH (and NaOH). To illustrate an average wood from thinning of a forest are combusted. Provided that all K, Na, S and Cl are brought to vapour phase potassium and sodium is sub-stoichiometric i.e. all have formed KCl, NaCl, K_2SO_4 and Na_2SO_4 provided the time and temperature are in the right range (see Table 1).

If all the alkali were available for aerosol formation the mass concentration can be calculated to 207 mg/Nm^3. That is however not the case. Some alkali are retained in the grate ash, some has deposited on fly ash particles and some has deposited on surfaces in the gasifier and in the combustor. A correlation between K and the amount of aerosol has been found to be

$$\text{aerosol}\left\{\text{mg}/\text{Nm}^3\right\} = 813 \bullet \left\{\%\text{K}\right\} - 69\left\{\text{mg}/\text{Nm}^3\right\} \quad \textit{Stenholm (1996)}$$

Normal wood chip	Wood, % of dry matter	Moles in vapour phase	Concentration in exit flue gas, ppm
S	0,05	0,0156 (29 ppm)	4
Cl	0,02	0,0056 (10,5 ppm)	2
K	0,1	0,0256 (48 ppm)	0
Na	0,015	0,0065 (12 ppm)	0

Table 1. Resulting vapour fraction Na, K, SO_2 and HCl from combustion of wood provided all Na, K, S and Cl have formed aerosols. Aerosols are not considered vapour fraction here. Conditions: 10,6% O_2 in flue gas, 537,5 mol flue gas/kg wood. The aerosol formation and the resulting HCl and SO_2 concentration is calculated according to Christensen (1996).

The correlation applies for straw in one specific plant with 40-45% potassium retained in the bottom ash. It indicate however to expect an aerosol amount in the order of 5-10 mg/Nm^3 (4-8 ppm) with a low alkali fuel in ordinary combustion and most likely a lower value for 2-stage gasification/combustion.

The aerosol size would be under 1 µm. The mean diameter for aerosols formed during combustion of straw is in the range from 0,2 to 0,6 µm.

The different forms of potassium, KCl, K_2SO_4 and KOH have different melting points (770°C, 1069°C and 360°C respectively). A low melting point makes it less likely that the substance condensate in the gas turbine. KOH is therefor more desirable than KCl and K_2SO_4. The fuel should therefor be low in both alkali and in S and Cl in order not to form S and Cl containing aerosols.

Fuel characterisation

Chemical characteristics

Wood is made of the building blocks cellulose, hemi celluloses and lignin and some extraneous components (extractives and ash) which do not contribute to the cell wall structure.

Different wood spices have different mix of these components but the chemical composition of woods varies very little within the different species (see Table 2).

The woods for the test runs will not be selected on basis of their content of C, H, O and N because of the very little variation found in the laboratory and in practice application. The heating value on dry basis is also very stabile and will not be taken into consideration in the selection of fuels.

The ash content does influence on ordinary combustion by fouling the heat surfaces and in the case of direct fired gas turbines fouling the turbine blades. The ash content does however varies between different wood spices and in different parts the tree. Table 3 is an example of a Danish investigation, *Heding (1995)*.

% of dry matter	C	H	N	Ash
Larch[1)]	49,7	5,9	0,15	0,72
Beech[1)]	48,7 - 49,9	5,6 - 5,9	0,17 - 0,27	0,62 - 0,75
Fir[1)]	51,0	6,1	0,10	0,49 - 0,66
Spruce[1)]	50,2 - 52,1	5,0 - 6,0	0,14 - 0,58	0,64 - 1,93
Bark[1)]	52,6	5,2	0,73	6,17
Eucalyptus chips[2)]	50,4	6,0	0,17	1,76
Eucalyptus [3)]	48,5	5,9	0,28	0,75
Poplar[4)]	49,9	6,1	0,29	1,36
Willow[4)]	47,7	5,7	0,43	1,45

Table 2 Proximate composition of different wood species.

[1)] Sander (1995) [2)] Feldmann (1988)

[3)] Domalski (1987) [4)] Reisinger (1996), different sources.

% of dry matter	Spruce	Birch
Leaves/needles	5,1	5,4
Branches	1,9	1,2
Bark	3,2	2,2
Stem	0,6	0,4

Table 3 Ash content in different wood parts

There is not a good correlation between ash content and alkali content, but in general wood with low ash content is low in alkali.

In order to comply with the strict restriction on alkali to the turbine the wood have to have a very low content of alkali (potassium and sodium). Not all wood species have the same alkali content and not all part of the same wood have the same content of alkali.

In order to differ the alkali content in wood it can be divided into three sections (discarding the leafs):

- inner wood (stem and branches)
- cambium (the growing layer outside the stem and the branches) and
- bark.

Wood needs Na and K for its growth but it is not a part of the building blocks (cellulose, hemi celluloses and lignin). The alkalis will during the growth of the tree migrate towards the growing part - the cambium, where its needed. As a consequence the growing part of the tree and the bark contains more alkali then the stem wood and young trees contains more than older trees. There are very little data to support the statement above.

% (mass) of dry matter	K [1]	K [2]	Na [1]	Na [2]	S
Larch	0,102	-	0,0044	-	0,05[1]
Beech	0,13 0,15	-	0,0036, 0,0060	-	0,029[1] 0,05[1]
Fir	0,077	0,050 0,080	0,004	0,0018	0,02[1]
Spruce	0,060-0,17	0,010 0,020	0,0032- 0,051	0,0008	0,02- 0,09[1]
Oak	-	0,12	-	0,0021	-
Stem wood	0,043		0,0020		0,024[1]
Birch[4]	0,0275		0,0028		-
Eucalyptus[3]	0,042		0,022		0,01
Poplar[3]	0,33		0,0011		0,05[4]
Willow[3]	0,10 -0, 37		0,022 -0,0 45		0,03[4]
Bark	0,22	-	0,0320	-	0,08[1]
Bark, mixed[5]	0,21		0,0190		0,08[5]

Table 4 Alkali and sulphur content in different wood species.

[1] Sander (1995).
[2] Rowell (1984).
[3] Dayton (1995).
[4] Reisinger (1996).
[5] Schmidt (1993).

The wood specimens used in (1) and (3) is chipped whole trees unless otherwise stated. There were no information on the specimens refereed in (2), but the lower values indicate absence of bark. (4) is wood with out bark.

Wood from coast near surroundings has an elevated Na content (0,036-0,051%) due to salty winds from the sea.

The test fuels

The list below indicates the rank of wood according to the alkali content, the wood with the lowest content is listed first:

1. *Wood from secondary wood industry (larger/older trees without bark)*
2. *Wood chips from conifers (fir/spruce)*
3. *Wood chips from broad leafs (oak/beech/birch/eucalyptus)*
4. Wood chips from early thinnings (more bark).
5. Bark.
6. *Short rotating crops (willow/poplar).*

The fuels 1,2,3 and 6 will be the test fuels in that order.

Physical characteristics

Wood fuels are available in practical all sizes from powder and shaving to 200 mm pieces. The vast majority of wood fuel are wood chips in the size range 3 mm to 100 mm from thinnings in woods.

The size distribution of the fuel does influence on combustion properties. It is usually the fine particles <3 mm which causes difficulties (feeding problems, pressure drop on grates and carry over). Large particles gives a more stable combustion.

In Denmark wood chips are sized in 3 mm diameter, 7 mm diameter, 8 mm slot and 45 mm diameter. In 1993 18 samples from nine locations in Denmark were sized with the following result:

Sieve	Wt.% retained	Min. observation	Max. observation
45 mm hole	3.5	0.5	13
8 mm slot	23.6	10	32
7 mm hole	60.2	49	77
3 mm hole	8.0	2	12

Table 5 Wood chip size in 1993, Denmark.

For practical application only one separation is made - particles under 5 mm are discarded.

The water content in wood can vary from 10 to 60% of total mass. The low water content are found in processed wood waste from the secondary wood industry such as joineries, carpenters and chip board manufactures, and the high water content in fresh cut wood.

Within these two broad categories there are wide a range depending on the time the trees have been laying before chipping and the climatic conditions.

Wood waste

Wood waste from secondary wood industry is mostly made from large trees (>20 cm diameter for broad leafs and >15 cm diameter for conifers) dried to a water content between 8 and 20%. A typical value is 12% water of total mass which is the equilibrium at room temperature and 60% RH. The wood waste comprises of saw dust, shavings, rejects and cut offs. There is no bark. Saw dust and shavings are either too small or have too large surface-volume proportion which gives a fluctuating gasification in conjunction with the larger wood pieces.

Due to the particular size distribution with dust and other fine particles a relatively high fraction has to be removed (sieved) in the preliminary test.

The transport weight will vary considerably depending on size distribution. A value about 250-350 kg/m^3 is considered most likely (saw dust is about 200 kg/m^3, shavings is about 90-110 kg/m^3 and wood pieces is about 300-400 kg/m^3).

The alkali content is expected to be 0,01-0,05% of dry matter.

Wood chips from conifer

Wood chips are mostly made from thinnings in the woods, i.e. from tree with a diameter of less than 10 cm. An other source is the branches from clear cuts. The diameter is also less than 10 cm. The water content in the fresh cut wood is between 55-65% and it decreases until June to about 35-45% if the trees have been laying in the wood since the winter. The average water content in the wood chips is about 55%.

Wood chips made from first thinning is not wanted because it is anticipated that it will contain more alkali. The alkali content is expected to be 0,05-0,2% of dry matter.

The transport weight is about 320 kg/m^3 (wet).

Wood chips from broad leafs

The average water content in the wood chips is about 45%. The transport weight is about 400 kg/m^3 (wet).

The alkali content is expected to be 0,1-0,2% of dry matter.

Energy crops

Willow and poplar are the two most common energy crops in the northern Europe. The water content in the fresh cut energy crop is about 50% and it is not stabile in storage (self ignition frequently occurs). The high alkali content makes energy crops to the least likely candidate for preliminary testing. The alkali content is expected to be 0,1-0,4% of dry matter.

The transport weight is about 350 kg/m^3 (wet).

Handling and storage

All the fuel for the test run on one fuel has to be delivered before the test commences in order to secure a proper sampling. A proper sampling is a least 11 samples each of 10 litre taken even in the pile. If more than 5% (mass) of the particles is more than 100 mm the samples has to be of 20 litre each. The samples are mixed and reduced in volume by cone and quartering (sample built into cone and spilt into equal quarters and opposite quarters recombined). The laboratory samples has to be 3,5-4 kg. This laboratory sample is for the complete analysis (K, Na, S, Cl, ash% and water%).

The storage has to be protected against rain either by indoor storage or by covering with a waterproof material. The storage has to be placed on a paved surface or on a waterproof material to avoid contamination with water (primarily fuel 1) and earth.

The fuel has to be well mixed before test runs if it has been stored in wet condition (the wood chips, fuel 2 and 3). During storage water evaporates from the inside of the pile and condensate further out which would give fluctuation in water content during the test runs, if it is not properly mixed. The preliminary classification in under and over 5 mm does not constitute for mixing. The mixing should be carried out on a clean surface with a bulldozer.

If the pile of wet fuel is stored more than 48 hours, it has to be mixed again before gasified. If it is stored more than a week six new samples have to be taken for determined the water content.

Logistics and costs

Fuel 1, wood waste from secondary wood industry, is not for sale on the open market. The "producers" have in most cases a arrangement with a wood pellet producer or they burn it themselves. There are several large producers within 100 km from the test facility and the price would be around 70 ECU/ton, 15% water. Ordering has to be made a least 14 days before use. Contact has to be established sooner in order to find a suitable supplier.

Fuel 2 and 3, wood chips from conifer and broad leave are available from a number of locations within 30 km. The price is about 40 DKr/GJ (40 ECU/ton, 55% water) for a truck load of 20 m^3 (6,4-8 ton). 5 m^3 is about 45 ECU/ton. Delivery within few days.

Fuel 4, willow or poplar, can be purchased on the open market to a similar price as ordinary wood chips. Ordering has to be made a least 14 days before use hence the supply is limited.

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