Bio Fuel Oil - Upgrading by Hot Filtration and Novel Physical Methods

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ABSTRACT

The primary objective of the R&D project was to support demonstration of a bioenergy scheme, where bio fuel oil (BFO) is employed as boiler or engine power plant fuel. At this stage quality improvement of the BFO is technically the critical factor related to pyrolysis liquid production. The principal technologies studied were hot filtration of pyrolysis vapours coupled to a pyrolyser, and preparation of microemulsion from BFO. The first aims in reducing solids content and alkali metals in BFO. The second aims in enabling use of BFO in existing equipment (small boilers, diesel engines) without major modifications. Related to BFO utilisation, experimental work in full-scale boilers and laboratory scale was performed. Basic data concerning use of BFO as power plant Diesel engines was generated. Markets for BFO were analysed.

Total of 5.8 tonnes of pyrolysis liquid was produced for utilisation tests and for quality improvement work within this project from forest residues and pine sawdust, which are considered industrially relevant feedstocks. Hot vapour filtration is a very efficient method to remove particles from the pyrolysis vapours and to improve the quality of the product liquid. The most critical parameters are filtration temperature, face velocity and particulate loading. Microemulsion technology, which would make it possible to use BFO and mineral oil mixtures in existing heat and power generating systems without major modifications, was also developed. The most influential process variable in emulsion preparation is surfactant concentration. EHS (environment, health and safety) aspects were also considered. In order to assure customers that a product is safe for shipping, storage and use, the health and safety aspects of a product must be evaluated.

Basic combustion data related to BFO utilisation in boilers and Diesel engine was generated in laboratory scale. The combustion fundamentals of droplets composed of pure pyrolysis oil, as well as of BFO-based emulsions and mixtures were examined. Experiments were performed at both ambient and high-pressure. Eight different fuels were examined for a total of about five hundred tests. The combustion of carbonaceous residuals from all samples was diffusion limited. Use of BFO in medium scale heating boilers was developed. Performance and emissions of CO, NOx, and particulates were measured in two industrial boilers (200 and 500 kW) modified for the purpose. Based on earlier and the current boiler combustion tests it is concluded that BFO can be effectively combusted using properly modified simple and relatively inexpensive pressure atomisation equipment and emissions reduced to acceptable levels. In order to assess the current limitations to the use of BFO in a light-duty Diesel engine, a series of tests were carried out with a stock single-cylinder, without any modification and/or pre-treatment of the fuel. Reliable operation was recorded with BFO-Diglyme blends, with a BFO content up to 37.5% in volume. Micro-emulsions of BFO in No.2 Diesel were also used.

Based on the market analysis, it is obvious that the replacement of light fuel oils will give more economic incentives than replacing heavy fuel oils.

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1. OBJECTIVES OF THE PROJECT

The **primary objective** of the R&D project is to support demonstration of a bioenergy scheme, where bio fuel oil (BFO) is employed as boiler or engine power plant fuel. BFO has potential in becoming a competitive bioenergy alternative in these markets.

A successful introduction of a new liquid fuel on the energy market will be very difficult because of the low quality of the present BFOs. At this stage quality improvement of the BFO is technically the critical factor.

The market has to be approached in stages. The approach is illustrated in Figure 1.1. The first stage preferably has to be a single heavy fuel oil (HFO) boiler, where BFO is used. Both production and utilisation should preferably be within one organisation. Once the technical problems have been overcome, it will be possible gradually to widen the market to eventual projected end-users, boilers and diesel power plants.

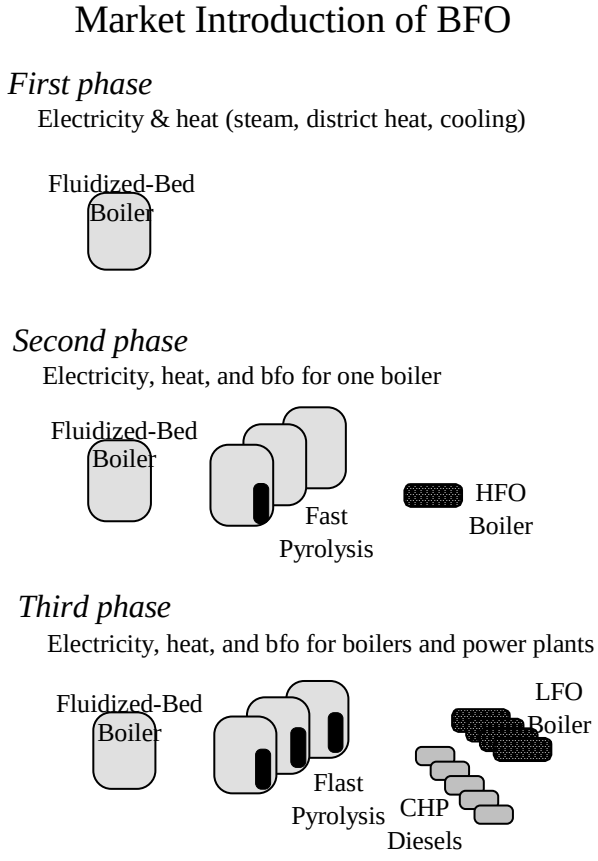

Figure 1.1 Market introduction of BFO

BFO may be envisioned to replace either light (LFO) or heavy fuel oil (HFO). Typically these oils are used as boiler and diesel power plant fuels. European prices for LFO and HFO are presented in Figures 1.2 and 1.3.

Fortum (a partner) and Birka Energi (a co-funding partner) are both considering utilising the technology as part of their future plans. These companies have estimated that there may be industrial opportunities in Europe, in which BFO may be viable.

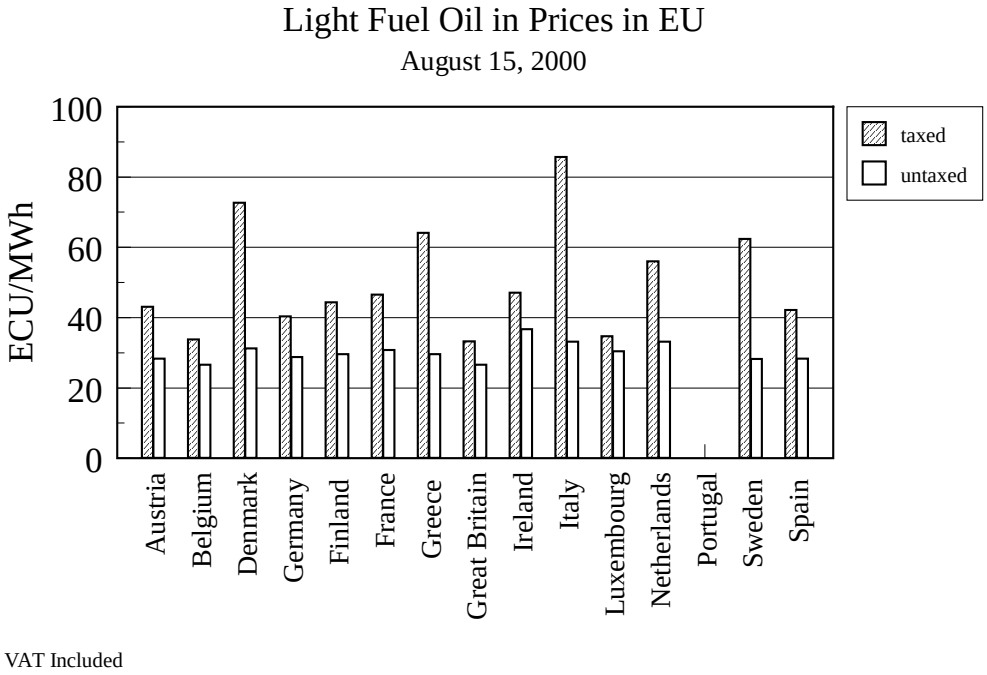

Figure 1.2. LFO prices in Europe/1/

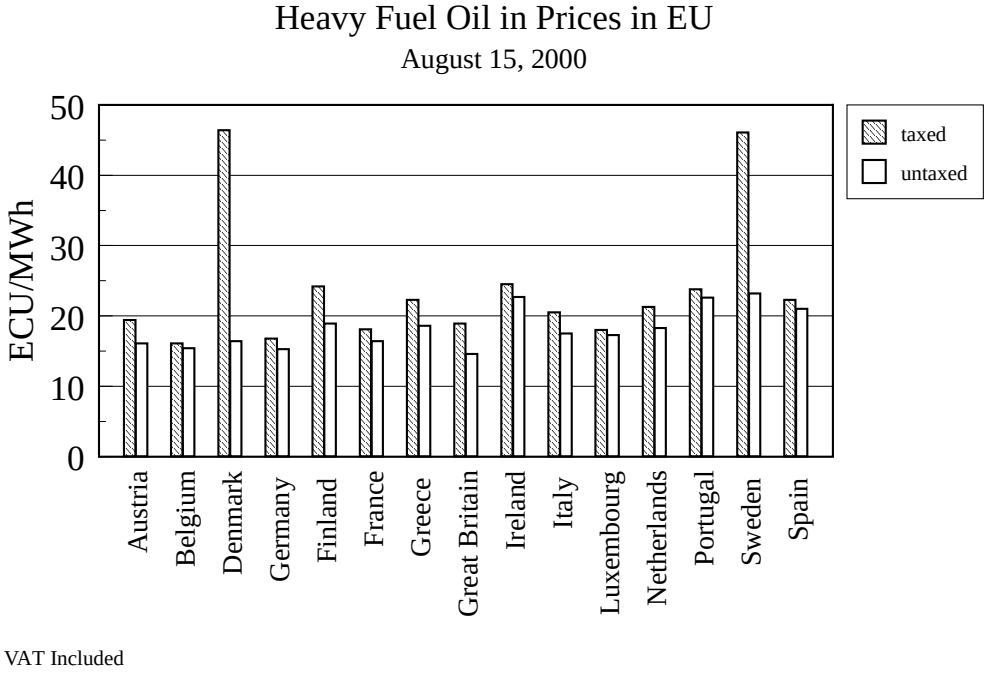

Figure 1.3. HFO prices in Europe/1/

BFO has been proposed also as a diesel power plant (DPP) fuel. There is very little experience of the application, and technical uncertainties with this concept are considerable.

BFO fired diesel power plant has been compared to a commercial Rankine power plant and to a HFO fired DPP in small scale, at 2 MWe (Figure 1.4). The scale is generally speaking considered uneconomic for conventional power plants, although some power plants of these types have been built down to 1 MWe. However, the comparison is done in small scale to emphasise the potential of BFO diesel power plants.

Two costs of electricity (COE) functions are shown for the BFO - diesel power plant. BFO production capacity is varied between 9 and 60 MWth of wood input. It may be seen that competitiveness of the diesel power plant is quite dependent of pyrolysis plant capacity. When the pyrolysis plant capacity is increased from 9 to 60 MWth (fuel input), the DPP becomes competitive below 5 000 annual operating hours compared to the Rankine plant.

Note that the COE is very high at this small capacity. A typical COE in a large (< 250 MWe) natural gas fired combined-cycle would be around 35 EUR/MWh. A typical wood fired Rankine combined heat and power (CHP) power plant may have a COE of around 40 EUR/MWh in Scandinavia.

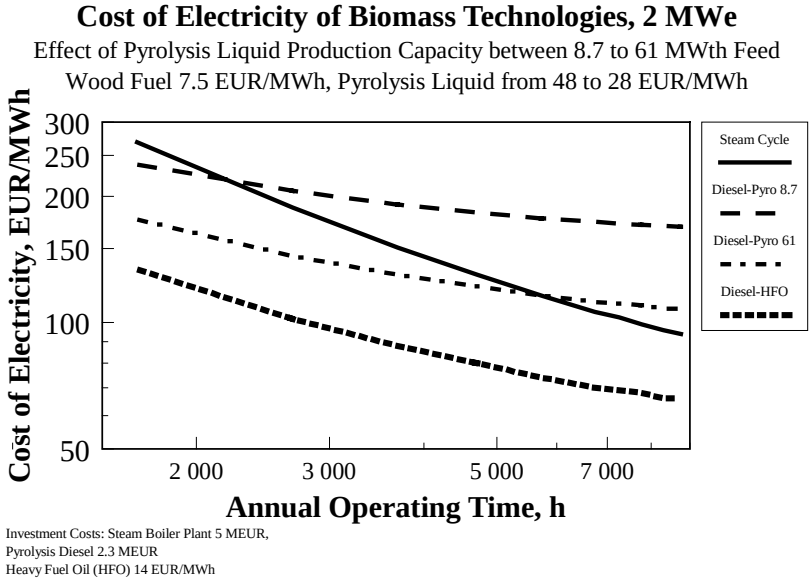

Figure 1.4. Bio-power alternatives

As a reference COE for a HFO fired DPP is also shown. The low COE shown is the ultimate objective for a pyrolysis fired DPP. HFO diesel power plant is the lowest cost alternative in this capacity range. Therefore, if BFO production cost will get close to HFO price, electricity production would be feasible.

Following objectives for the R&D project have been defined:

- To increase the market value of BFO by improving BFO quality as fuel
- To improve the utilisation of BFO in power plants and boilers.

These objectives are pursued in several tasks. Following **technical objectives** have been defined for the project:

- To develop hot vapour filtration at process development unit (PDU) scale to remove solids from BFO. The present solid content of 0.5 to 2 wt% will be reduced to <0.1 wt%.
- To develop microemulsion technology, which would make it possible to use BFO and mineral oil mixtures in existing equipment without major modifications. Three emulsions will be manufactured and characterised in laboratory analysis.
- To maximise organic yield by varying key process parameters (temperature, residence time) for pyrolysis of three feedstocks (forest residues, pine sawdust, and straw).
- To develop bio fuel oil handling and storage procedures, and to study the health and safety issues related to industrial use of BFO.
- Four BFO and derivatives will be employed in laboratory scale equipment to characterise their fundamental combustion behaviour.
- To develop use of BFO in medium scale heating boilers. Performance and emissions of CO, NOx, and particulates will be measured for two BFO in a 200 kW boiler.
- To support the development of a BFO as power plant engine fuel by generating basic engine performance and emission data.
- To determine the competitiveness of BFO as heating oil in Finland and Sweden.

2. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE PROJECT

2.1 TASKS AND METHODS

The objectives listed in the previous section were pursued in following tasks:

- Hot filtration for pyrolysis vapours (task 1)
- Microemulsions (task 2)
- BFO production and quality (task 3)
- Handling and storage of BFO, and heath and safety issues related to BFO (task 4)
- Fundamental behaviour of BFO in combustion (task 5)
- Medium size boiler tests (task 6)
- Engine tests (task 7)
- Market opportunities for bio fuel oil (task 8)
- Co-ordination (task 9)

Project structure is shown in Figure 2.1.

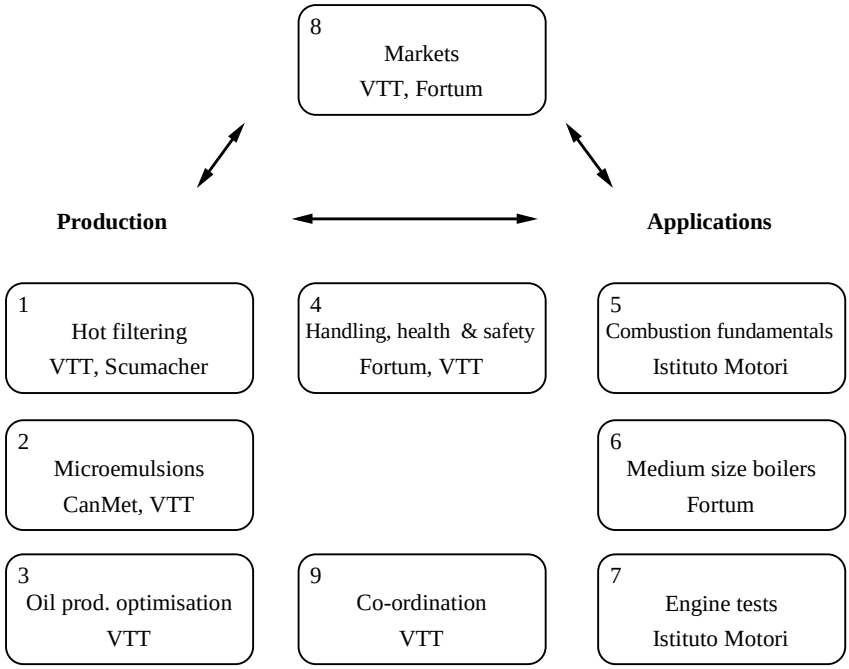

Figure 2.1. Project organisation and task participants

The project has been successful in all tasks carried out. The tasks of the project were carried out within the planned schedule with minor exceptions.

In task 1, hot vapour filtration of pyrolysis vapours (HVF) was carried out as planned. Two long-term test runs in the bench-scale unit (Figure 2.2) were carried out, and the

necessary data for scale-up was generated. Design of a slipstream HVF system was carried out, and the equipment (including a scrubber with pumps and heat exchangers, HVF vessel, necessary piping and instrumentation) was installed (Figure 2.2). Note that the investment costs were paid outside the current project. The HVF system was operated integrated to the Process Development Unit (PDU), which is described related to task 3.

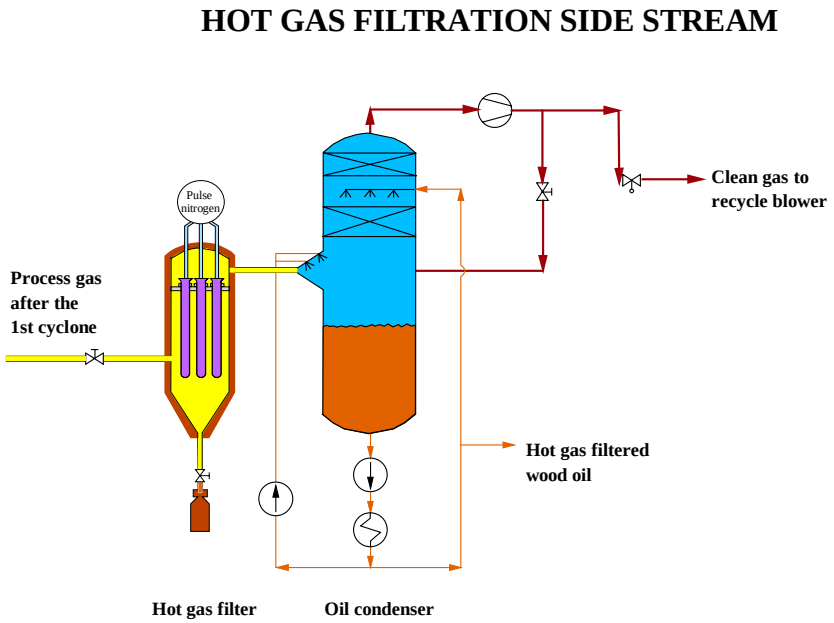

Figure 2.2. HVF integrated to the PDU (not shown)

In task 2, several different microemulsion samples were prepared (Figure 2.3) and analysed. Some of the samples were also used in utilisation tests. The task was carried out as planned.

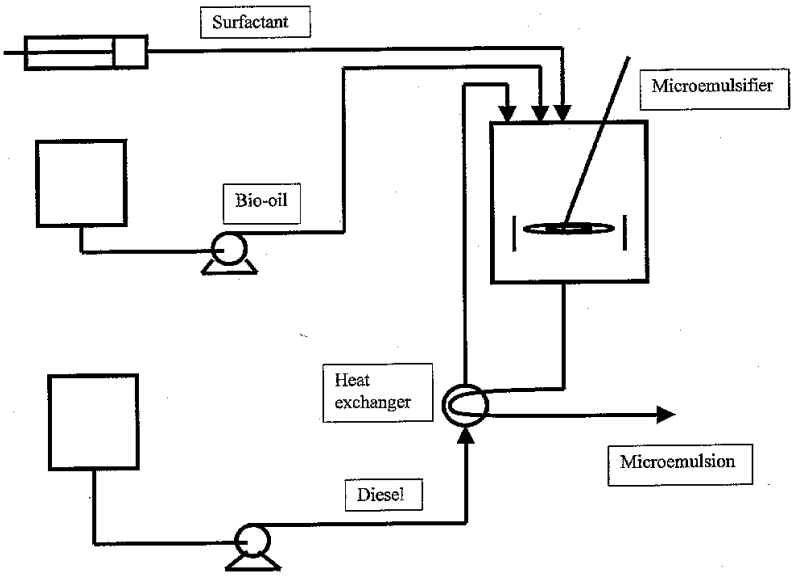

Figure 2.3. Bench-scale emulsifier

In task 3, a PDU pyrolysis system was operated with three woody feedstocks. In addition, a bench-scale unit was operated with straw. Total of 5.8 tonnes of pyrolysis liquid was produced for utilisation tests and quality improvement work. Solvent addition was studied to improve the stability of BFO. The task was carried out as planned.

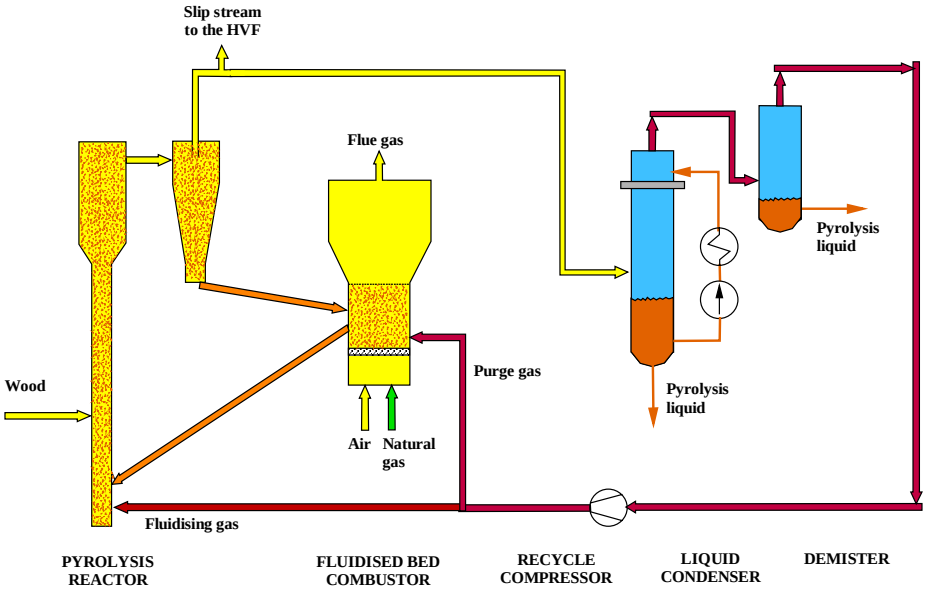

Figure 2.3. PDU pyrolyzer

In task 4, a manual for the handling procedure of BFO was prepared. The task was carried out as planned.

In task 5, an experimental system to study the vaporisation/combustion in both ambient and high-pressure conditions of BFO droplets was developed and set-up. Two chambers to study BFO droplet combustion in high-pressure conditions were designed and built up. The experimental set-up is shown in Figure 2.4. Experimental work was carried out with eight BFO and mixture samples in about 500 experiments as explained in detail in section 2.2. The data from the work are used to study basic combustion characteristics of BFO both for boiler and engine applications. The initial plan was slightly expanded to increase the applicability of the results generated.

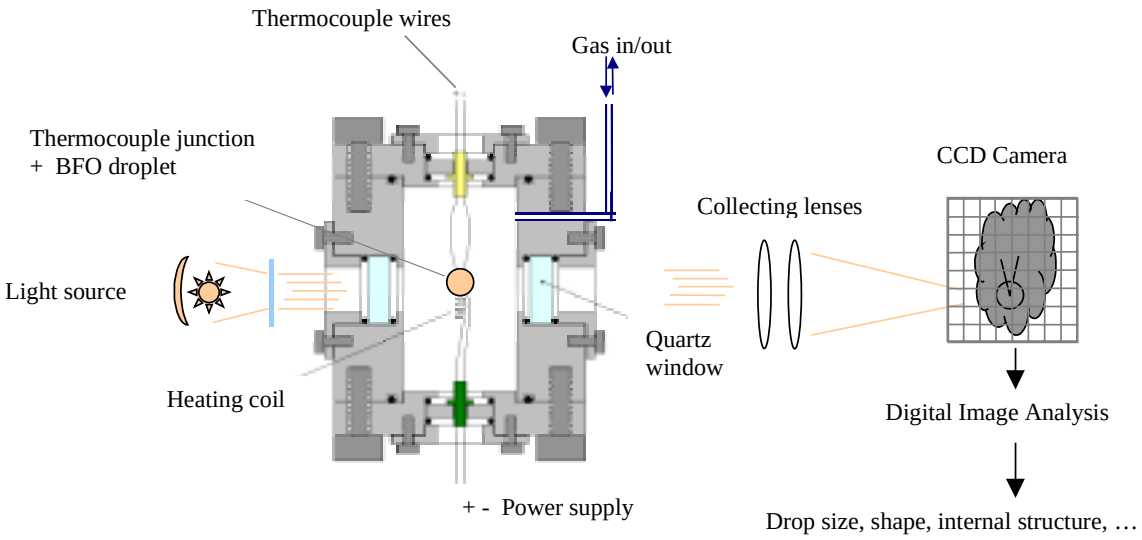

Figure 2.4. Single droplet high-pressure chamber test system

In task 6, a 500 kW boiler for BFO combustion was modified in addition to the existing 200 kW (Figure 2.5). The work has been carried outside the current project. Both boilers were used in combustion of BFO, and performance and emissions from the experiments are reported. The initial plan was slightly expanded to take into account the results generated after the preparation of project work plan.

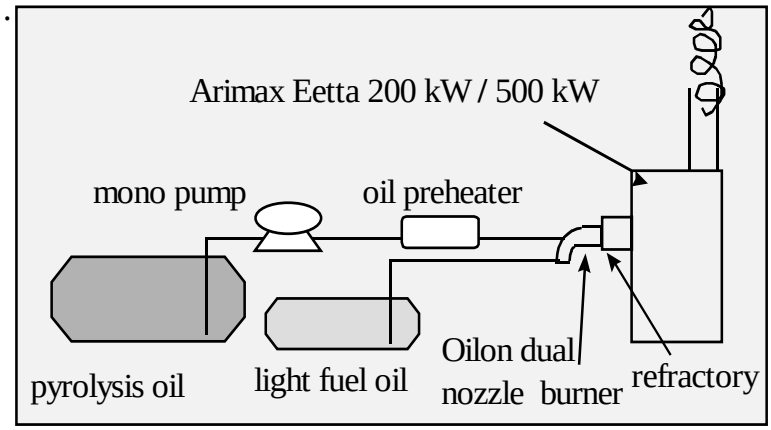

Figure 2.5. The combustion system

In Task 7, two systems were employed: a spray injection rig and a single cylinder diesel engine.

A transparent test rig, allowing spray visualization has been set up, in order to perform tests on the behavior of BFO with a Diesel injection system. A single-orifice injector (Bosch KBL 76579/4 223 ϕ= 0.4 mm) was used, coupled to a Bosch pump type PF. An electric engine drove the pump. Tests were performed at 1000 rpm, with an opening

pressure of the nozzle of 200 bar. Further injection trials included a 4-holes injector (Bosch KBEL 108 P 25, ϕ=0.28 mm).

A high-speed digital imaging system (*Motionscope* by Redlake) has been used for recording the spray evolution in time. Typical speed was 4000 frames per second, with an exposure time of 50 μs per frame. Spatial resolution was 100×98 pixel. A cw Ar+ laser has been used as the light source, allowing the most effective and versatile handling of the illumination.

The spray, injected in the transparent test rig, was visualized with back-illumination: this optical set-up essentially allowed appreciating the extension of liquid part of the spray, together with some characteristic parameters (e.g. the break-up length or the spray cone angle).

The engine used for the tests is a production *Ruggerini RP170* single-cylinder engine with a displacement of 747 cm^3 (bore = 100 mm, stroke = 95 mm, compression ratio = 18:1). The injection system consists of a *Bosch* pump type P and a *Bosch* nozzle (model *DLL 160SA570W5L*, 4 holes, Φ = 0.28 mm, 160°). This engine has been previously characterized in terms of internal fluid dynamics by LDV measurement. While basically a stock engine, multiple accesses are provided in the cylinder head for the visualization of injection and combustion events. A fast sampling valve allows additional sampling of species. Standard analyzers were used for exhaust gas analysis: a FID for HC, a chemiluminescent analyzer for NO_x, and a NDIR analyzer for CO.

Tests have been carried out with blends of Pine Oil and Diglyme (12.5%, 25%, 37.5% and 50% in volume of BFO). The sample used for the blends was the pyrolysis oil produced at VTT PDU from Finnish Pine (see Table 2). Two different emulsions with 30% (in weight) BFO in No. 2 Diesel Fuel were supplied by CANMET and tested accordingly. A Hydrotreated Diesel (HDT) fuel was used as a reference.

The task was carried out as planned.

The task 8. Heavy fuel oil (HFO) markets in Sweden and light fuel oil (LFO) markets in Finland and Sweden give good market potential to initiate production. The options to the customer, who wishes to switch to a renewable fuel, is investments of 1 - 10 M FIM for solid combustion system, or 30-500 k FIM for BFO modification to an existing system. Although there are remaining technical uncertainties, the system, where BFO is used, appears intersting for many users. The task was carried out as planned.

Task 9, co-ordination, has been carried out as planned. Five project meetings were held.

2.2 RESULTS

2.2.1 Hot filtration for pyrolysis vapours (task 1)

The objective of the task was to develop hot vapour filtration, first at a bench scale unit (capacity 1.5 kg/h) and at process development unit (PDU, capacity 20 kg/h) side stream to remove solids from BFO. The aim was to reduce the solid content of 0.5 - 2 wt% to <0.1 wt%.

Particulate removal by hot vapour filtration of pyrolysis product gas is a potential method to upgrade the product liquid. However, the technical implementation of the filtraton is difficult because pyrolysis vapours can easily condense on surface of particles. When condensation takes place filter dust cake will become sticky leading to poor cleaning of filters. This can further lead to permanent dust cake and finally to clogging of the filter.

The filtration of pyrolysis vapours has been studied and developed in bench scale in previous pyrolysis projects of VTT (/2/) and results have been promising. The filter has been operated successfully and this encouraged to continue the development. The bench scale filter was designed to be capable to filter 50...80 l/min (NTP). The previous work focused on design, construction and preliminary technical testing of the filter. This project continued optimisation of the operation of the filter and on long term stability of the filter. The final goal was to install hot vapour filter to the PDU scale pyrolysis unit of VTT Energy, to test the technical performanceof the filter and finally carry out filtration tests.

The long term hot vapour filtration tests with the bench scale pyrolyser showed that the filter could be operated continuously and stable operation conditions could be reached. These results were used as a background data in design of the larger scale filter. Pressure drop over the HVF is shown in Figure 2.6.

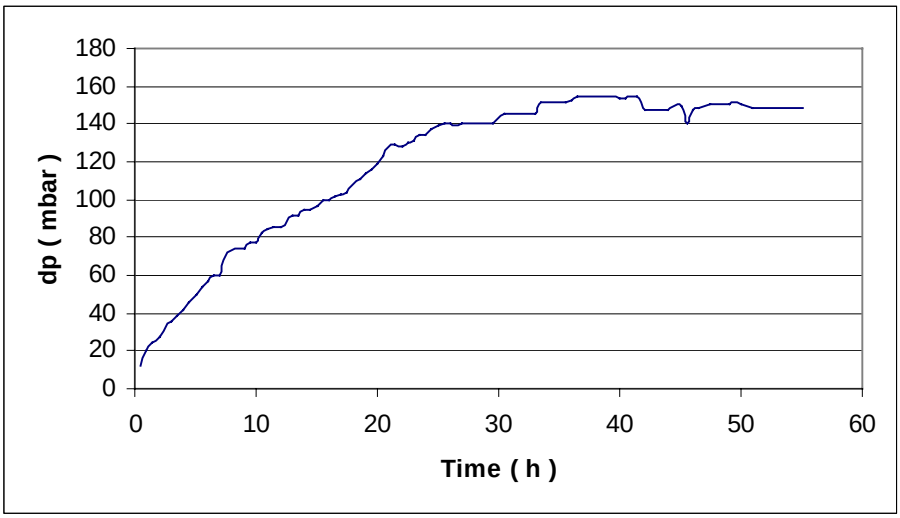

Figure 2.6. Pressure drop over the hot vapour filter (test run 10/2).

The next step was to design and construct the PDU scale filtration system to be connected to PDU scale pyrolyser. The filter was designed to be installed to slip stream of the pyrolyser. The slip stream installation required reliable and stable gas flow control system. This was arranged by constructing a separate scrubber after the filter. Scrubber was followed by continuously operating gas low measurement and control system.

The filter unit for PDU scale pyrolyser was constructed simultaneously with gas scrubbing and gas flow control system. The basic design of the filter was the same as was used in bench scale tests. It was designed to be capable to handle 150-500 l_n/min (30...100 % of the total gas flow of the pyrolyser). The principal aim was to use the filter for a 30 % slipstream, around 150 l/min.

The filter was equipped with three one-meter long, ceramic, candle filter elements. Filter elements were selected and delivered by USF Schumacher. The filter unit was equipped with electrical heating to compensate heat losses.

Initial experiments were carried out with a 170 l/min slipstream. As the pressure drop increased continuously, tests were carried out with full gas flow of about 450 l/min. However, the both tests with 100 % gas flow lead to very similar result than with 30…50 % gas flow: efficient solids removal but inefficient filter cleaning (filter dust detachment).

After detailed evaluation of the results the conclusion was that reasons for continuously increasing pressure drop in those two different cases (30…50 % and 100 % gas flow entering into the filter) were most probably different. It was also very evident that in the case of 30…50 % gas flow the particulate loading was not representative (compared to total gas flow).

Based on these conclusions the next tests were planned based on about 30…40 % gas flow. In addition, a special attention was focused on correct particulate loading of the gas entering the filter. Gas flow was adjusted to 150 l/min to limit the surface velocity. Filter was operated at 515^{o}C. Pyrolyser was fueled by forest residue derived fuel.

Filter operated as designed: pressure drop of the filter increased linearly as long as the pulse cleaning was done. Pulse cleaning was capable to detach filter dust cake and dust cake was removed from the bottom of the filter vessel. Some partial self-detachment was also detected (some part of the dust was felt into the bottom of the filter vessel without any pulse cleaning of the filters). The pressure drop of the filter is presented in Figure 2.7.

It was demonstrated that hot vapour filtration is very efficient method to remove particles from the pyrolysis vapours and to improve the quality of the product liquid. The extremely low solid content of the product liquid is reported in Tables 2.4 and 2.5. However, the successful implementation of the filtration requires optimised filtration conditions.

USF Scuhmacher examined the filters after the tests. The filters were in good condition, and no irreversible phenomena had taken place. Report of the analysis is attached as Appendix 8 to this report.

The most critical parameters are filtration temperature, face velocity and particulate loading. The particle size distribution also plays important role in successful design of the filtration process. When filtration conditions are favourable a good filtration performance can be met. This includes not only the efficient particulate removal but also efficient detachment of dust cake from the filter surfaces by high pressure pulsing and discharging the dust from filter vessel. Hot vapour filtration of pyrolysis vapours was also demonstrated successfully in PDU scale.

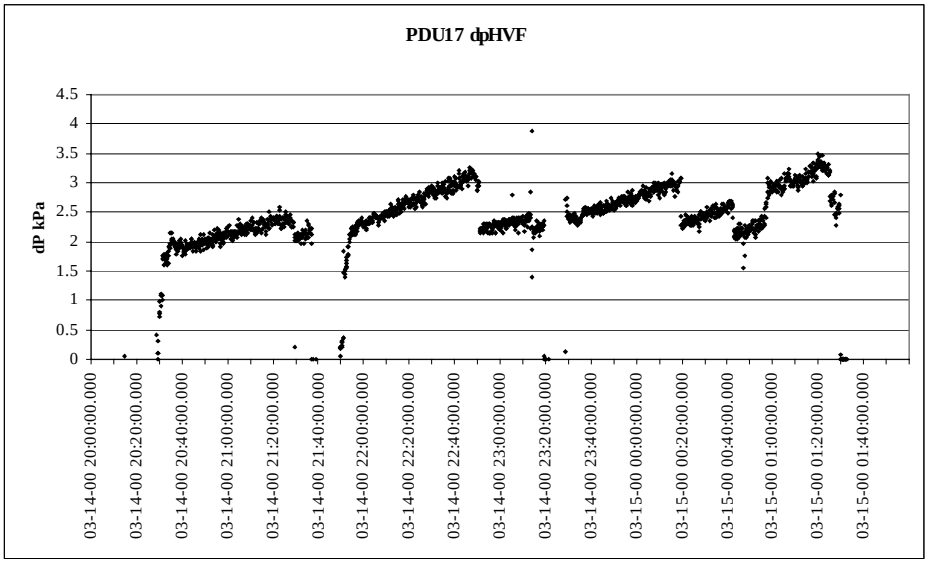

Figure 2.7. Pressure drop of the filter (PDU 17).

2.2.2 Microemulsions (task 2)

The objective was to develop microemulsion technology, which would make it possible to use BFO and mineral oil mixtures in existing heat and power generating systems without major modifications. Three emulsions were to be manufactured by CETC (CANMET Energy Technology Centre) and characterised in laboratory analysis.

If stable bio-oil in diesel emulsions could be produced acidity and viscosity problems would be mitigated. Also physical properties of emulsions would be closer to that of the continuous phase (diesel in this case) than that of bio-oil itself, and the negative effects of ash and char in bio-oil would be less because of dilution by diesel. In addition, low NOx emission could be expected. When 5-15 vol% water was emulsified into seed-oil bio-fuel, NOx and soot emissions were reduced in a series of engine tests. These were explained by improved atomization possibly through microexplosion and lower combustion-chamber temperature /3/. Because bio-oil has a high water content, similar advantages could be expected from bio-oil in diesel emulsions.

CANMET Energy Technology Centre (CETC) established that stable emulsions could be prepared from pyrolysis derived bio-oil and regular diesel fuel using appropriate

surfactants /4/. Emulsions so produced are extremely stable depending on surfactant concentrations. The emulsified products are referred to as BDMs for bio-oil diesel mixtures in this report.

Ranges of process conditions required for successful Bio-diesel mixtures (BDMs) were established in a batch emulsifier prior to the present work. It was found that product emulsions were prone to form precipitate over time. Although the precipitate is easily redispersed into the emulsion by gentle shaking, its presence is undesirable in fuel. Thus, it became necessary to establish the ranges of lowest surfactant concentration and power input required to produce stable BDMS. A series runs were done to determine the relationship between process conditions and emulsion stability. Some characteristics of resulting microemulsions are discussed as well.

Five process variables were examined: bio-oil concentration, surfactant concentration, residence time, motor speed and emulsification temperature. For the experimental design, the following ranges were given: bio-oil concentration (wt % of total feed) 10 and 30%, surfactant concentration (wt % of bio-oil) 1 and 5 %, residence time 5 and 20 min, motor speed 800 and 1750 rpm, and temperature 50 °C and 70 °C.

However, as the analyses progressed, it became evident that operating temperature had little effect at the ranges investigated and they were eliminated from further consideration. Residence time (L/h) and power input (kW) at corresponding motor speed were combined as one variable to give power input per unit volume (kWh/L) of BDM processed. This procedure reduced five variables to three: bio-oil concentration (wt % of total), surfactant concentration % of total) and volumetric mixing power input (kWh/L).

Sedimentation rates are important. It was found out that sedimentation begins within six hours for the least stable case. It was also shown that the induction period of sedimentation can be changed. In one case there was no sedimentation even after 42 days.

An example of the sediment contours is shown if Figure 2.8, where 10 wt% BMDs is shown. It was shown that although more stable BDMs can generally be expected when surfactant concentration and energy input are high, excessive power input beyond optimal values can lead to less stable emulsions. The most influential process variable is surfactant concentration. When surfactant concentration is insufficient, emulsions are not stable even when produced under extremely high power input. The optimal locus follows the least power and surfactant concentration and thus represents the most economical locus for emulsion production.

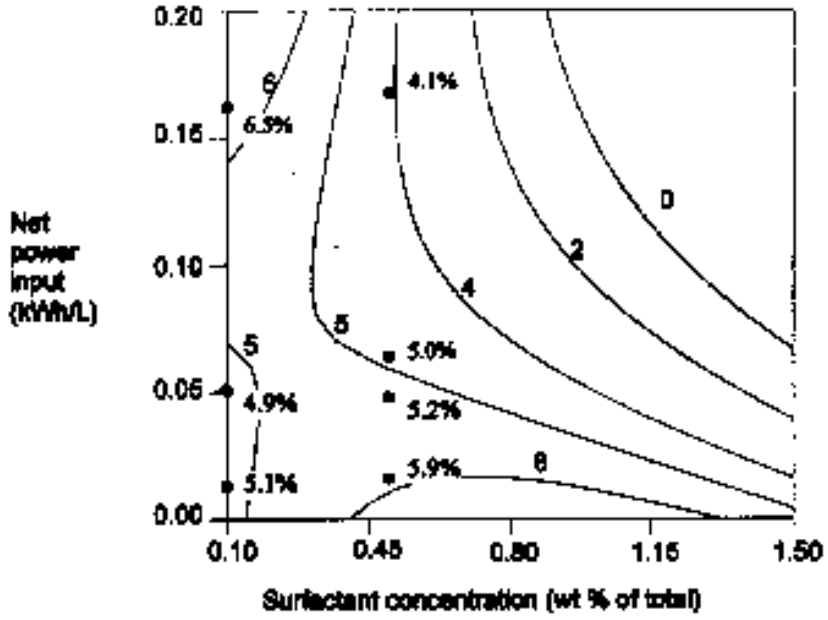

Figure 2.8. Sediment contours for 10 % BDMs

The principal conclusions were:

Bio-oils in diesel emulsion fuels were produced and their stability investigated. Results were analyzed using a statistical model. A quadratic response surface model agrees well with experimental results. Dominant parameters are bio-oil and surfactant concentrations and power input, and there are optimal loci for different bio-oil concentrations that minimize the final costs of emulsified products.

Fuel properties such as cetane number, viscosity and corrosion were characterized. Ensyn pyrolytic oil had a cetane number of 20.6±1.3. Usually it is not easy to determine the cetane number of pyrolytic bio-oil due to its poor combustion characteristics. However, when emulsions were formed it was possible to do so by linear interpolation. The viscosity of emulsified fuels was best described by Einstein's equation for dilute solid dispersions.

2.2.3 BFO production (task 3)

The objective is to determine optimum values for key process parameters (temperature, residence time) for pyrolysis of three feedstocks (forest residues, pine sawdust, and straw). The organic yield is maximised using optimum parameters. The organic yield is expected to be above 65 wt% for pine sawdust without the hot vapour filter (HVF). Both the PDU and laboratory scale (150 g/h) units are used for this task.

Pyrolysis liquid or bio fuel oil (BFO) has been estimated to be the lowest cost liquid biofuel /5/. The estimated production costs have to be further decreased, its quality has to

be improved, and the production of a homogenous liquid has to be demonstrated industrially, before BFO is a marketable product.

Woody biomasses (forest residues, pine sawdust) are considered industrially relevant feedstocks for potential BFO production in Scandinavia. Wood samples were pyrolysed within this task to produce pyrolysis liquid for utilisation tests (tasks 5, 6, and 7 within this project) and for quality improvement work (tasks 2 and 3).

It has been shown earlier /6/ that fast pyrolysis of straw, and the subsequent use of the pyrolysis liquid as a diesel power plant fuel, is economically attractive in Denmark. As part of a work, which aims in developing technologies for this opportunity, fast pyrolysis tests in a laboratory scale pyrolyzer with straw were carried out.

A summary of the tests being reported is shown in Table 2.1. The hot filter was operated part time during runs 13, 15, 16, 17, and 18. Other tests provided liquid for utilisation tests and product improvement work.

Table 2.1. Summary of experiments 10-18, FR = Forest residue

	Time	Feedstock	Production kg
PDU10	Dec 1998	Pine 1	535
PDU11	Mar 1999	Pine 2	1036
PDU12	Jun 1999	Pine 3	707
PDU13	Sept 1999	FR 95	422
PDU15	Dec 1999	FR 95	158
PDU16	Feb 2000	FR 95	1212
PDU17	Mar 2000	FR 95	793
PDU18	May 2000	FR 2	906

A summary of yields, when wood fuels are used is shown in Tables 2.2 and 2.3. Note that both organic and pyrolysis water yields are calculated for dry feedstock. The yields are also shown in Figure 2.9. The yields are calculated based on weighted overall mass yields during runs. The amounts produced in the runs range between 540 and 1210 kg.

Table 2.2. Liquid yields based on dry feed, pine feedstock

	PDU10	PDU11	PDU12
Organic yield wt%	66.9	63.2	59.2
Pyrolysis water wt%	10.5	8.9	11.1
Liquid yield wt%	77.4	72.1	70.3

Table 2.3. Liquid yields based on dry feed, forest residue feedstock

	PDU16	PDU17	PDU18
Organic yield wt%	46.3	49.5	43.1
Pyrolysis water wt%	12.7	14.7	12.6
Liquid yield wt%	59.0	64.2	55.7

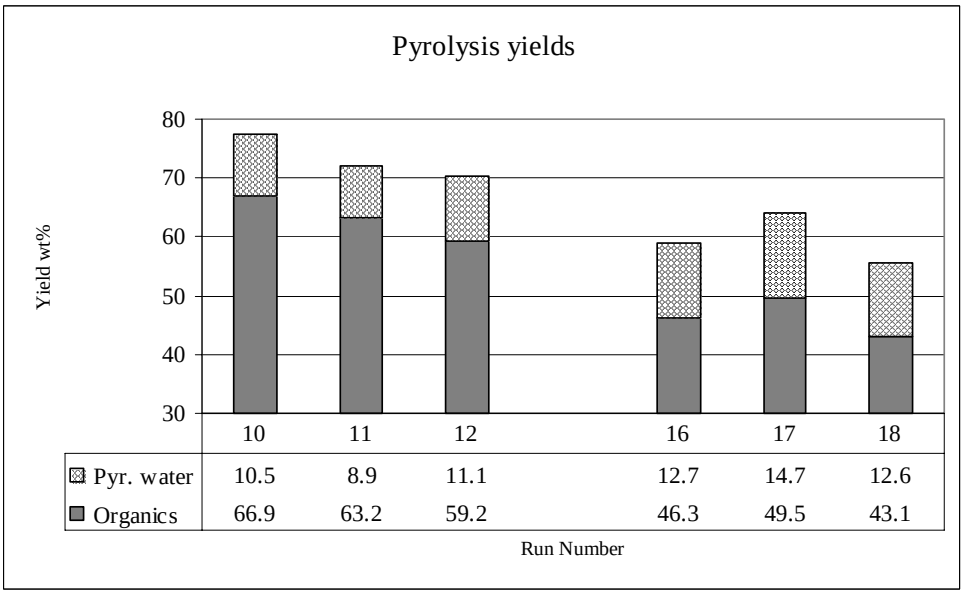

Figure 2.9 Liquid yields based on dry feed, wood feedstock

The effect of ash content of wood feed on the organic liquid yield is shown in Figure 2.10. The yield is based on the mass of the whole liquid produced, and it ranges between 530 - 1210 kg. The decrease in the yield of organic liquid is clear, as the ash content of the feed is increased. The result is also important because although process parameters were varied during runs, ash content appears to explain much of the variation.

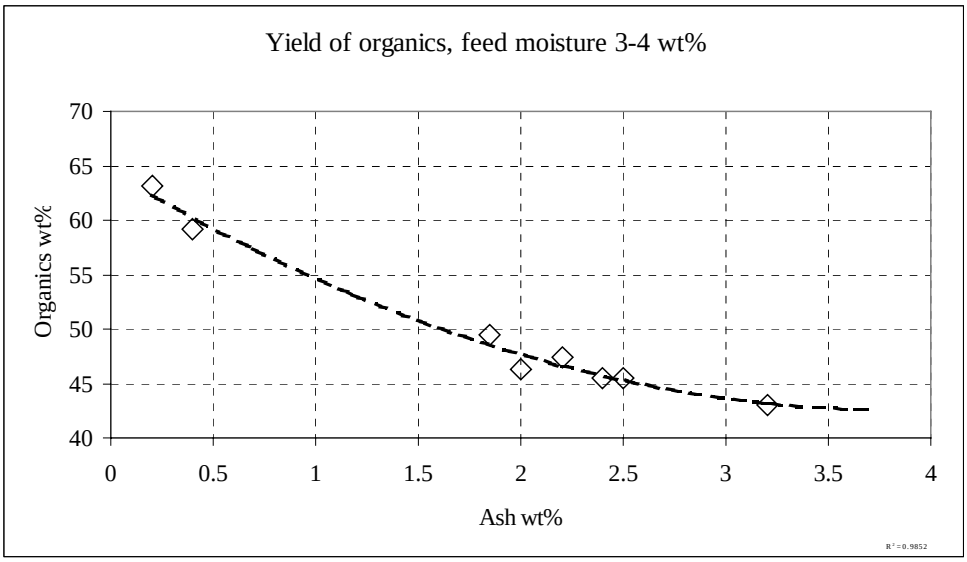

Figure 2.10. Organic liquid yield as a function of feed ash content

The effect of moisture on the organic liquid yield using pine feed is shown in Figure 2.11. A potential explanation for this feature is a decreasing heat flow into the organic matrix, because more water has to be evaporated before pyrolysis may proceed. The result has considerable practical consequences. If the correlation presented is valid also for larger facilities, a quite dry material must be used for pyrolysis to reach a high organic yield. An alternative would be to use an even smaller particle size to improve heat transfer. However, this may be even more expensive than drying the feed to low moisture content.

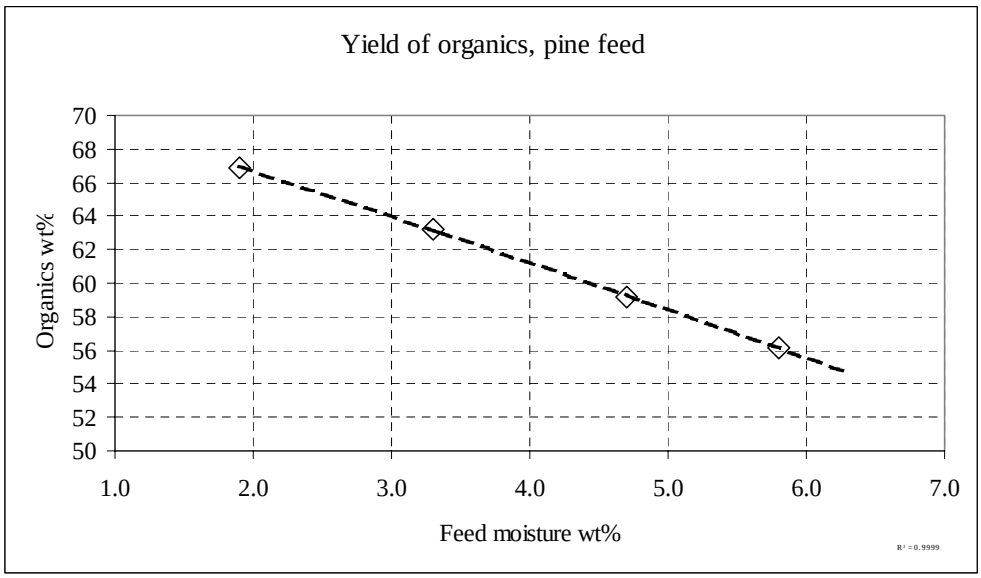

Figure 2.11. Organic liquid yield as a function of feed moisture content

Danish straw samples were converted in the laboratory pyrolyzer. It should be noted that the yield data is not directly comparable to the PDU data given above. Because of different

scale, solvents are used in the laboratory unit to determine liquid yield. The feed particle size is also considerably smaller. Finally, the reactor types used in this task are also different. Among other, these factors contribute to differences between the two systems.

Organic liquid yield as a function of reaction temperature is shown for straw in Figure 2.12. Four different straw samples have been converted. The correlations are shown for two different samples: one with natural ash composition and one that has been water washed to reduce the amount of alkali metals. Removing a large fraction of alkali metals (80 % of potassium in the "washed" sample) increases the yield of organic liquid considerably.

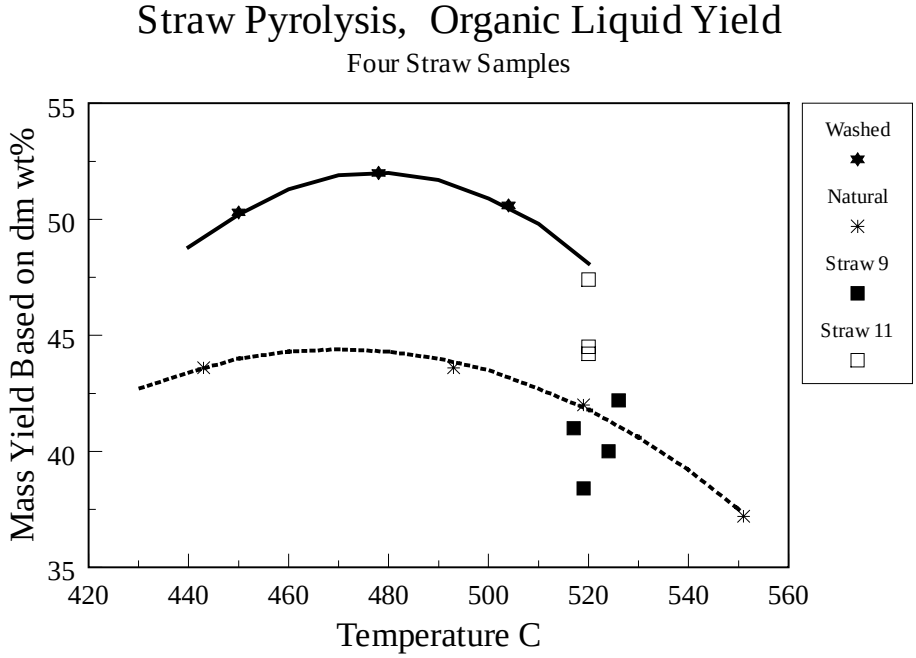

Figure 2.12. Organic liquid yield in straw pyrolysis

Conclusions from the task are summarised:

All the objectives of the task were met. Total of 5.8 tonnes of pyrolysis liquid was produced for utilisation tests and quality improvement work. It was found that a relatively high reaction temperature of 530 °C produced the highest liquid yield in the PDU unit, when forest residue fuel was used as feedstock. In the bench scale unit the maximum liquid yield for straw was around 480 °C. The residence time was not varied. A shorter residence time than the present 2 seconds in the PDU might have been more favourable. However, it could not be shortened because of excessive carry over of fines to the liquid, if reactor gas velocity would further have been increased. The organic liquid yield was 66 wt%, when a dry (2 wt% moisture) pine feed was used. Finally, the unit PDU unit was operated successfully in a steady-state mode to enable hot filter operation.

2.2.4 BFO quality (task 1, 2 and 3)

Biomass pyrolysis liquid product may be used as a fuel oil substitute. Combustion tests performed using different scale burners (for example, task 6) and internal combustion engines and gas turbines have demonstrated that the oils could be burnt efficiently in standard or slightly modified equipment. These tests also identified several challenges in pyrolysis liquid applications resulting from their properties.

Pyrolysis liquids are typically dark-brown organic liquids. The physical properties of the oils as well as methods for their measurements are described in several publications (for example /7/, more references in an appendix to this report). These properties result from the chemical composition of the oils, which is significantly different from that of petroleum-derived fuels.

The thermal cracking of pyrolysis vapors during hot filtration, although reducing the oil yield, has a beneficial impact on the oil quality /for example, 8/. It causes size reduction of oligomeric chains, which not only affects the oil viscosity but its combustion chemistry as well. Diesel engine tests performed on crude and hot-filtered oils show a substantial increase in burning rate and a lower ignition delay for the latter. The main reason for this improvement in combustion quality is thought to be the structural change expressed as the lower average molecular weight.

Polar solvents have been used for many years to homogenize and to reduce viscosity of pyrolysis liquids /9, 10/. The addition of solvents, especially methanol, also shows a significant effect on oil stabilization. The rate of viscosity increase for the oil with 10 wt% of methanol is almost 20 times less than for the oil without additives /11/. It is postulated that solvent addition can impact the oil viscosity by three mechanisms:

1. physical dilution without affecting the chemical reaction rates;
2. reducing the reaction rate by molecular dilution or by changing the oil microstructure;
3. chemical reactions between the solvent and the oil components that prevent further chain growth.

The chemical reactions that can occur between the pyrolysis liquid and methanol or ethanol are esterification and acetalization. Though thermodynamically non-favored, they can proceed to a significant extent if appropriate conditions are applied. In such a case, in addition to the decrease in viscosity and in aging rate, they also lead to other desirable changes like reduced acidity, improved volatility and heating value, and better miscibility with diesel fuels. Considering the simplicity, the low cost of some solvents (methanol) and their beneficial effects on the oil properties, this method seems to be the most practical approach to pyrolysis liquid quality upgrading.

Pyrolysis liquids are not miscible with hydrocarbon fuels, but they can be emulsified with diesel oil with the aid of surfactants. A process for producing stable micro-emulsions, with 5 - 30% of pyrolysis liquid in diesel has been developed at CANMET Energy Technology Centre (task 2). These emulsions are less corrosive and have showed promising ignition characteristics.

PDU **pine pyrolysis liquids** have been good-quality single-phase liquids (Table 2.4). Solids content is typically 0.1 - 0.3 wt%, when the particle size of the feed is below 3 mm.

Lower solids contents, 0.02 - 0.1 wt%, in PDU runs 4 - 6 have been obtained for a smaller particle size. Ash content is typically 0.2 - 0.3 wt-% with 10 - 30 ppm K+Na. Water content varies with feedstock moisture from 16.3 (feedstock moisture 3.3 wt-%) to 21.4 wt% (feedstock moisture 5.8 wt%). Density, heating value and viscosity vary also with the water content.

Table 2.4. Fuel oil analyses of PDU pine liquids.

	PDU4	PDU5	PDU6	PDU7	PDU8	PDU10	PDU11	PDU11	PDU12	PDU13	PDU13 KS
Solids, wt-% (abt. 1 µm)											
ethanol	0.03	0.02	0.11		0.20	0.25	0.29	0.35	0.06	0.14	0.02
methanol:CH3Cl, 1:1											
pH	2.4	2.3		2.3	2.6			2.6	2.5		2.6
Water, wt-% (ASTM D 1744)	17.0	20.4	19.6	19.8	21.4	15.7	16.3	16.6	21.3	21.4	25.4
Viscosity , cSt (ASTM D 445)											
40°C					35					36	
50°C	28	16	24	28	21	29	32	31	23		9
Density (15°C), kg/dm3 (ASTM D 4052)	1.24	1.23	1.23	1.24	1.22	1.24	1.24		1.23		1.19
Heating value (HHV), MJ/kg (DIN 51900)	18.7	17.3	18.5	17.9	17.8		19.0	19.1	18.2		17.2
Lower heating value (LHV), MJ/kg	17.2	15.8			16.3		17.6	17.7	16.6		15.6
Ash, wt-% (EN 7)	0.03	0.02			0.02	0.02	0.03		0.03		0.018
CHN, wt-% (ASTM D5373-93)											
C	45.7	42.8			43.5		46.7	46.6	44.9		41.6
H	7	7.1			7.10		6.7	6.7	7.4		7.5
N	< 0,1	<0.1			< 0.1		0.1	0.1	< 0,1		< 0,1
Alkali metals, mg/kg											
Na	6.1	4.1									
K	16	6.5									
Mg	5.4	15									
Ca	23	49									
Cl, mg/kg											
S, mg/kg											
Conradson carbon, wt-% (ASTM D 189)	16	14		17							
Flash point, °C (ASTM D 93)											
Pour point, °C (ASTM D 97)	-19			-24							

The feedstock for PDU16-20 experiments was **forest residue**. A large amount of extractives in bark and needles in the feed yielded two distinct oil phases (chemical composition in Figure 2.13). Physical properties are shown in Table 2.5.

The surface phase (30 - 40 vol% of the whole liquid product) contained most of the extractives. This surface phase was of wax-like foamy material its polarity (low in oxygen) being much lower than that of the bottom phase. The main compound classes in the surface phase were fatty acids, resin acids, resin and fatty alcohols, sterols, and phenolic substances. Because of high amount of neutral substances the water content and the amount of water-soluble compounds are low.

The bottom phase (60 - 70 vol%) resembles a typical softwood pyrolysis liquid. The differences to other softwood oils are higher water and ash contents and the presence of a small amount of extractives. Alkali metals in ash act as catalystsin pyrolysis producing high water content. In addition, the surface phase rejects water to the bottom phase.

Table 2.5. Physical properties of forest residue liquids.

	PDU16		PDU17			PDU18		PDU18 hot-filtered		PDU37/00	
	top	bottom	top	bottom	17F bottom	top	bottom	top	bottom	top	bottom
Solids, wt-% (abt. 1 µm)											
ethanol			2.7	0.1							
methanol:CH3Cl, 1:1					0.0	1.1	0.1	0.0	0.0	0.8	0.1
pH	3.1	3.1	3.3	3.2	3.2	3.4	3.4	3.3	3.2	3.52	3.35
Water, wt-% (ASTM D 1744)	27.0	24.6	13.8	27.7	29.4	13.1	31.4	12.1	32.9	13.0	30.9
Viscosity , cSt (ASTM D 445)											
20°C	16	16					26		26		33
40°C			153	18	17			191	11		12
Density (15°C), kg/dm3 (ASTM D 4052)		1.190		1.205	1.206	1.126	1.184	1.136	1.183		1.175
Heating value (HHV), MJ/kg (DIN 51900	16.7	17.6	27.0	16.4	17.8	27.8	16.3	25.9	15.3	25.5	
Lower heating value (LHV), MJ/kg	15.1	16.0	25.3	14.7	16.2	26.1		24.1	13.6	23.9	
Ash, wt-% (EN 7)	0.3	0.2	0.4		0.2	0.3	0.1	0.2	0.2	0.1	
CHN, wt-% (ASTM D5373-93)											
C	40.4	42.5	59.9	40.1	38.8	57.3	36.2	57.7	36.2	57.6	
H	7.5	7.6	7.8	7.5	7.5	7.8	8.0	8.0	7.9	7.7	
N	0.3	0.2	0.2	<0.1	0.4	0.3	0.3	0.3	0.3	0.3	
Alkali metals, mg/kg											
Na	10	10			5.2	41	7	27	19		15
K	95	98			130	86	85	30	75		88
Mg	130	140			150	36	74	16	91		65
Ca	630	540			630	430	400	240	390		360
Cl, mg/kg	<100	<100									
S, mg/kg	290	310									
Conradson carbon, wt-% (ASTM D 189)		17.5									
Flash point, °C (ASTM D 93)	45	42					40		50		
Pour point, °C (ASTM D 97)	-15	-12									

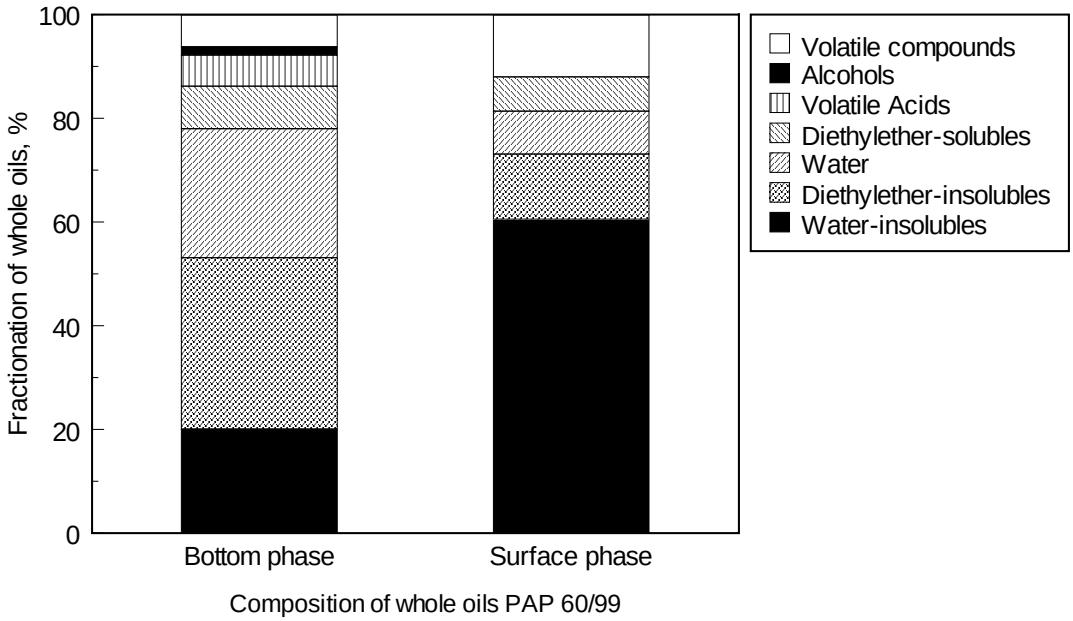

Figure 2.13. Chemical composition of the bottom and surface phases of forest residue liquid. Fractionation is based on water and solvent extractions.

The main differences between pine and straw liquids are:

- Water yield is higher for straw because a higher amount of alkali metals catalyzes water formation reactions. The water yield is a function of alkali metal content in the feedstock.
- Straw yields in a smaller water-insoluble fraction due to a smaller amount of lignin in the feedstock.
- Straw produces more acids because of its composition. The proportion of acetic acid is larger for straw liquid than for pine liquid.
- Straw pyrolysis liquid contains more methanol, aldehydes and ketones than pine pyrolysis liquid.

The main differences between pine and forest residue liquids are:

- Liquids produced from forest residue are multi-phase containing an extractive-rich upper layer.
- Extractives in forest residue liquid demand a more powerful solvent than alcohol. A mixture of a polar and neutral solvent is needed for solids determination.
- The bottom phase of forest residue liquid is very similar to that of pine liquid except of a small concentration of extractives and higher water content.
- Forest residue contains more ash, and alkali metals produces a high water yield. Alkali metals may be also cause the higher reactivity of forest residue liquid.
- Needles in forest residue produce high nitrogen content of the liquid.

Physical properties of liquids from **different producers** are presented in Table 2.5. Note that feed material for the different liquids is not known. Feed is known to affect liquid quality in addition to processing conditions.

Table 2.5. Physical properties of liquids from various producers.

Compound	Unit	Dynamotive	Pyrovac	Ensyn	BTG	Kiln tar	VTT
Water	wt-%	23	16	21	35	n.m.	31
Viscosity, @40°C	cSt	31	216	248	10,8	239	15,7
Solids	wt-%	0,672	0,845	3,392	0,397	11,4	0,06
pH		2,2	2,7	2,5	2,5	n.m.	3,0
Density	kg/dm3	1,22	1,25	1,25	1,20	n.m.	1,20
Heating value	MJ/kg	18,2	20,1	18,8	14,2	n.m.	16,1
Flash point	°C	49	93	89	55	n.m.	49
Vapour pressure	kPa	6	5	5	4	n.m.	5
Elemental anal. C	wt-%	43,9	50,1	45,9	36,5	79,1	37,0
Elemental anal. N	wt-%	0,1	0,3	0,2	0,1	0,2	0,4
Elemental anal. H	wt-%	7,5	7,1	7,3	8,0	9,9	8,0
Elemental anal. O	wt-%	48,5	42,5	46,6	55,4	10,8	54,6
Ash	wt-%	<0,01	0,16	0,03	0,02	0,07	0,29

The **hot-filtration study** (task 1) was focused on technical operation of the filter. Hence, no systematic study on the quality of oil was carried out. However, hot-filtration changes the oil quality as follows: increase in water, decrease in solids. Due to the high water content of the oil the stability test could not be carried out.

Emulsion samples from pine pyrolysis liquids were all in two phases. However, simple shaking of the emulsion can remix them. These emulsions were not true microemulsions because of a clear appearance of droplets above 1 µm size. In addition, emulsions looked unhomogenous. Samples from forest residue oil were the most stable microemulsions ever analysed. The droplet size of the whole sample is below 1 µm and the emulsion is in single-phase at least for 6 months storage.

The following conclusions can be drawn:

- Stability of pine pyrolysis liquids can be improved by adding water, methanol, or a mixture of these solvents.
- Liquids produced from forest residue are multi-phase containing an extractive-rich upper layer. The surface phase is high in extractives and solids and low in water, oxygen, and polar compounds. The bottom phase of forest residue liquid is very similar to that of pine liquid except of a small concentration of extractives and higher water content.
- Forest residue containing more ash, and alkali metals produces a high water yield. Alkali metals may be also cause the higher reactivity of forest residue liquid.
- Forest residue liquids are more reactive than pine pyrolysis liquids. The reactivity is highest during the first month.
- Needles in forest residue produce high nitrogen content of the liquid.
- Straw is high in alkali metals which causes high water yield. The chemical composition of straw yield also to higher amount of acids, especially acetic acid, and higher amount of methanol, aldehydes and ketones than pine pyrolysis liquid.
- Hot-filtration increases the water content and decreases the solids content of the liquid.
- Forest residue liquid yields in a stable microemulsion with light fuel oil.

2.2.5 Handling and storage of BFO, and heath and safety issues related to BFO (task 4)

The objective is to develop bio fuel oil handling and storage procedures for industrial applications, and to study the health and safety issues related to industrial use of BFO.

The work in this task concentrated on the following subtasks:

- Material Safety Data Sheet (MSDS): To determine chemical and physical-chemical characteristics of BFO to produce MSDS
- Other clearances concerning toxicology, ecotoxicology, handling, storage and product
- Exposures and emissions

The work started from determining the chemical and physical-chemical characteristics of BFO. Because properties of BFO differ from those for fossil oil, not all standard procedures developed for fossil oil could be used. In this work methods suitable for BFO tested at VTT by Oasmaa et al. /7/ and some methods for fossil oil were used. This work gave information and data to determine MSDS for BFO. Based on previous information feedstock, process conditions and processing of BFO determine mainly the properties of BFO. That is why content of various components and physical characteristics of BFO between different BFO producers varies a lot and sometimes between production lots of one producer.

The analysed BFOs that were made with fast pyrolysis method were compared to kiln-burned pine tar that is made by slow pyrolysis method. This was done to describe the difference between these two products and also to help in categorising BFO product. Kiln-burned pine tar has CAS and EINECS categories but for BFO they have not been defined.

BFO of different producers were analysed giving special attention to toxic, mutagenic and/or carcinogenic compounds (Table 2.6).

Table 2.6. Summary of the quantitative results of chemical characteristics

Compound	Unit	Dyna-motive	Pyrovac	Ensyn	BTG	kiln tar	VTT
C1-C6 acids	wt-%	4,2	4,4	6,5	6,4	0,4	5,1
Aldehydes and ketones	wt-%	2,5	1,5	1,2	2,2	0,1	1,3
Phenols	wt-%	4,9	5,2	1,8	3,3	4,7	2,8
EPA-PAHs	mg/kg	8	28	330	3	1030	2
VOC/monoaromatics	mg/kg	680	10	510	90	1860	200
VOC/2-methyl-2-butenal	mg/kg	100	<10	40	70	<10	70
VOC/furane	mg/kg	110	20	10	60	50	40

Acidity of BFO

As can be seen from Table 2.6 the total amount of detected C1-C6-acids as benzyl derivative from water phase show that BFO has some 5 wt-% acidic compounds. pH measurements in Table 2.5 show that BFO has strong acidic property while pH is 2-3. Authorities are more interested about the total acidity than single components.

Aldehydes and ketones of BFO

The total amount of detected aldehydes and ketones was below 5 wt-%. Amount of carcinogenic compounds like formaldehyde and acetaldehyde varied in measured samples between 0,01-0,84 wt-%.

Phenols

The total amount of detected phenols was below 6 wt-%. Variation between BFO produced by different producers exists. This may be due to use of different feedstock and process conditions.

EPA-PAH compounds

Most interesting results were measured in case of polyaromatic hydrocarbons. As can be seen from the table, the concentration of PAHs is a function of use of different feedstock and process conditions. As a reference kiln-burned pine tar has 500 times greater values compared to VTT's BFO. This is due to fast pyrolysis that apparently reduces formation of PAHs.

VOC compounds

The amount of volatile organic compounds varied as can be seen from table x. The variation can be interpreted to be due to different process conditions. Pyrovac's vacuum process seems to decrease the amount of volatile components.

EHS (environment, health and safety) aspects were also considered. In order to assure customers that a product is safe for shipping, storage and use, the health and safety aspects of a product must be evaluated. Much of this information can be obtained from products MSDS (material safety data sheet). This is required for all products which are sold in Europe together with its' EINECS (European Index of Existing Chemical Substances) number. Unfortunately the EINECS numbers for existing products do not reflect the exact nature of this new fast pyrolysis product.

Exposure measurements were also carried out in connection to a boiler test with 500 kW BFO burner used for half day test period. Burning temperature is about 800-900°C. Consumption of isopropyl alcohol that is used for cleaning of equipment is about 0,1-5 l/day. BFO made by VTT was pumped from 100 l barrels to burner. Also LFO was used as a support fuel in the beginning and end of test periods.

Summary of the results: Concentrations of hydrocarbons were low. Isopropyl had concentrations of 3-12 ppm that is 6% of the limit. Of aromatic hydrocarbons benzene concentrations were < 0,1 ppm that is less than 2% of limit, toluene and ethyl benzene concentrations < 0,1 ppm that is less than 1% of limit and xylene concentrations < 1 ppm that is less than 1% of limit.

Concentrations of PAH compounds were relative small. Concentrations of benzo(a)pyrene in fixed test points were <0,01 $\mu g/m^3$ that is less than 1% of limit. Naphthalene was the only compound that could be detected over limit of identification 0,6 $\mu g/m^3$ that is less than 1% of limit.

In boiler use of BFO temporary measured concentrations of carbon monoxide and NO_x were less than the limit of identification < 2 ppm for CO and < 0,5 ppm for $NO+NO_2$. The concentration of CO_2 was 0,01%.

- As a summary it can be said that the measured contaminant concentrations were small.

- During the measurements in the boiler room atmosphere could be detected a strong smell of tar and smoke was irritating. That's why one must take care of enough ventilation in the boiler room and site specific ventilation must be arranged.
- Disposable gloves that are used in handling BFO must be thick and they must be changed frequently.
- More measurements must be done to get more statistical information. Far going conclusions can not be made after one measurement day.

Materials. Because of acidity (pH 2-3) of pyrolysis liquids following recommendations for materials are suggested:

- Plastics or AISI 316 for storage
- Plastics, copper and its alloys (no abrasion), AISI 316 for piping applications
- AISI 316 or better acid-resistant steel for process equipment

Due to instability and reactivity of pyrolysis liquids following storage conditions are recommended:

- Air-free plastic or stainless steel containers
- Storage temperature 15 °C, but at least below 25 °C
- Constant slow propeller stirring

Following is recommended for handling:

- Air should be avoided
- Heating above 60 °C should be avoided
- Heating between 40-60 °C should be minimised to a few hours
- Hot surfaces has to be avoided

For poor-quality pyrolysis liquids following is suggested:

- Homogenising of the liquid with simultaneous addition of 5-10 wt-% methanol. A 1-2 wt-% addition of formic acid for homogenisation is not adequate.
- Slow constant propeller-type mixing provided during the storage.

2.2.6. Fundamental behaviour of BFO in combustion (task 5)

The objective of task 5 was to highlight, in a lab scale environment, the combustion fundamentals of droplets composed of pure pyrolysis oil, as well as of BFO-based emulsions and mixtures. As the utilisation of such fuels was foreseen in boilers and in Diesel engines, attention had to be given to the problem of formation and behaviour of unburned solid material, in order to avoid intolerable particulate emissions and operational problems.

The specific objectives of the task were:

1) Description of the thermal behaviour (heating, vaporisation and combustion features) of BFO and BFO derived fuel droplets at normal and high pressure conditions;

2) Study of the physical and chemical phenomena undergone by droplets (swelling, liquid phase pyrolysis inside droplet);
3) Study of the formation of carbonaceous residuals.

Two single-droplet combustion chambers were developed to study evaporation-combustion of single droplets up to 100 bar. Droplets composed of different fuels were suspended to a thermocouple or to a quartz fibre. Quartz windows permitted the optical access to the chambers. Both laser and halogen light sources were used to illuminate droplets during vaporisation, before ignition. The thermal behaviour exhibited by droplets was followed by means of high-speed digital imaging. About two thousands of frames were collected for each test. The acquisition velocity ranged between 400 and 4000 frames/s.

Eight different fuels were examined for a total of about five hundred tests. Experiments were carried out on a pure pine pyrolysis oil, two emulsions of forest residue oil (10% and 30%) in #2 diesel oil, an emulsion of 30% of pine oil in #2 diesel oil, a mixture of pine oil (30%) in diglyme. Reference tests were carried out on commercial Italian Diesel oil, on diglyme and on hexadecane. Diglyme was chosen for the good ignition property (cetane number 110-130) and for the very low sooting tendency; n-hexadecane (or "cetane") was tested because it is used in the standard procedures to evaluate ignition characteristics of Diesel engine fuels. The pressure ranged between 1 and 60 bar, the size of droplets between 400 μm and 1100 μm.

All fuels were easy to ignite at normal and high pressure. In the investigated experimental conditions, the environment temperature had a significant influence on the ignition delay: this was due mainly to the relevance of the physics of the process (heating and vaporisation of the fuel) respect to the chemistry in the pre-ignition phase. Also the influence of different heating rates on combustion phenomenology was investigated. The main effect resulted on droplet evaporation rate and swelling phenomena. The temperature of the chamber and the heating ramp influenced instead only marginally after-ignition processes.

Increasing the pressure, the swelling phenomena - typical of pure pyrolysis oils - exhibited a reduced intensity and completely disappeared at pressures higher than 20 bar. Mixture and emulsion droplets showed less marked swelling at normal pressure and the phenomenon completely disappeared already at 10 bar. However, strong bubbling and foaming were observed. The temporal sequence heating-swelling-vaporisation/bubbling/foaming-ignition was strongly dependent on the properties of the "carrier" fuel used in the preparation of the mixture or emulsions.

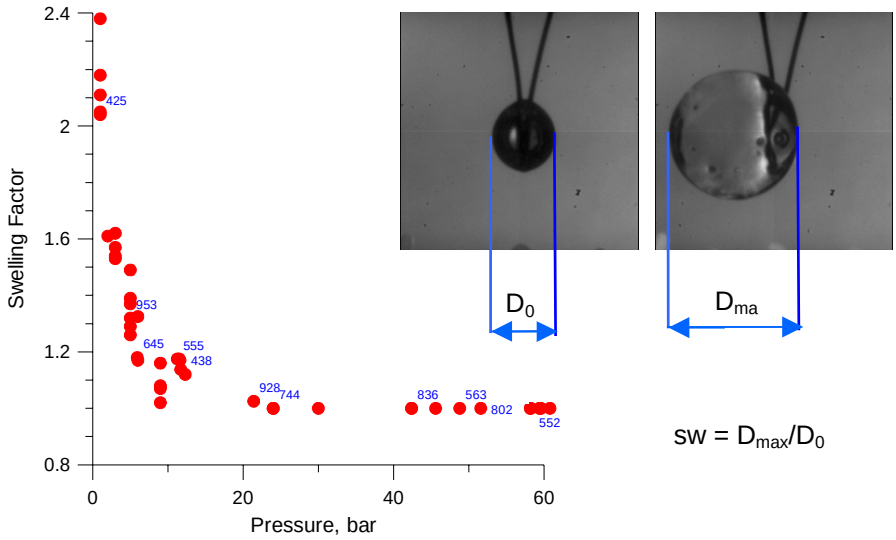

Figure 2.14. Swelling factor vs pressure for pur pine pyrolysis oil droplet

After ignition, both mixture and emulsions droplets underwent a diameter reduction that could be approximated with a D^2 law. Some difficulties arose for pure oil droplets due to the strong swelling that prevented a correct determination of the drop diameter. The droplets burning time (normalised respect to the drop diameter) decreased with pressure for all the samples. The liquid burning rate was around 1 mm^2/sec at normal pressure, increased to about 1.5 mm^2/sec at 12 bar and to 2 mm^2/sec at 45 bar.

All the samples, even if to a different extent, evidenced liquid-phase pyrolysis and the formation of a cenosphere during the last part of the liquid combustion. However, the formation of a solid residual, peculiar of pure oil droplets, was reduced in the case of emulsions and mixtures. Interesting enough, these samples gave rise to a smaller solid residual respect to what could be expected from the BFO content in the parent droplet. This was due to the different combustion properties of emulsions and mixtures when compared to pure BFOs. The other main parameter influencing cenosphere formation was, of course, the BFO quality and composition. The synergy between BFO quality and combustion properties can result in very surprising effects: in practice no solid residual was formed by the emulsion made with 30% pine oil in #2 diesel oil.

The pressure also played a role in the structure and shape of the residual since it forced the droplet/cenosphere surface in opposite direction respect to the internal pressure generated by the liquid vaporised in the droplet interior. At intermediate pressures, around 10 bar, the balancing between these forces produced "cocoon" shaped cenospheres when pure BFO was used. Pressure had a minor influence on cenosphere formation when emulsions and mixtures were used. This could be explained by considering their low content of oil and, hence, of "swelling" agent. An increase of the residual size with pressure was observed at 45 bar for the samples containing the higher oil concentration.

In the examined experimental conditions, the combustion of residuals from all samples was diffusion limited. The cenosphere burning rate was, hence, determined essentially by the particle surface extension.

2.2.7 Medium size boiler tests (task 6)

The objective is to develop use of BFO in medium scale heating boilers. Performance and emissions of CO, NOx, and particulates were be measured for BFO in 200 and 500 kW boilers.

The existing burner equipment that is normally used with light fuel oils has been optimized with a much higher heating value fuel than pyrolysis liquid (roughly double). This means that to achieve an adequate fuel / air mixtures and velocities, much less air is required for combustion. This causes the flame to expand in size and to extend to the end of the combustion chamber. It was observed that this type of flame is such that internal heating is not adequate to combust particulates and high molecular tars which increases emissions. In addition, since pyrolysis viscosity is higher than light fuel oils, a higher pressure is used which leads to drop blow through and higher particulate emissions.

The pyrolysis liquids produced at VTT from pine sawdust with water concentrations less than 24% gave a more stable flame in the 200 kW boiler. The 30% water content pyrolysis liquid produced from forestry residues could not be combusted cleanly in the 200 kW boiler system with the existing equipment but was found to give a good flame in the larger 500 kW boiler. Upon further comparison of the 200 kW and 500 kW burners that were used in this project it was noted that both use the same dimensions for the burner retention head. This means that for the larger loads in the larger boiler the relative velocities adjacent to the burner retention head are much greater giving a much better fuel / air mixture and a more stable and hotter flame.

From both a viscosity standpoint and a solids standpoint, both the forestry residue and pine sawdust fuels produced by VTT Energy were of sufficiently good quality to be combusted cleanly in light fuel oil boilers. The only notable emissions that are higher than for light fuel oils is that of particulates and tars. It is believed that once a burner is designed specifically for pyrolysis liquids, it will be possible to reduce further these emissions and combust these fuels cleanly in this size class. From a combustion standpoint, the most important emission is carbon monoxide (CO) which is shown in Figure 2.15 for the forestry residue sample from VTT. Carbon monoxide is an intermediate combustion product between the fuel itself and the final combustion product carbon dioxide. The lower the carbon monoxide, the more complete the combustion. The value shown in Figure 2,15 illustrates that the pyrolysis liquid was combusting cleanly in the system.

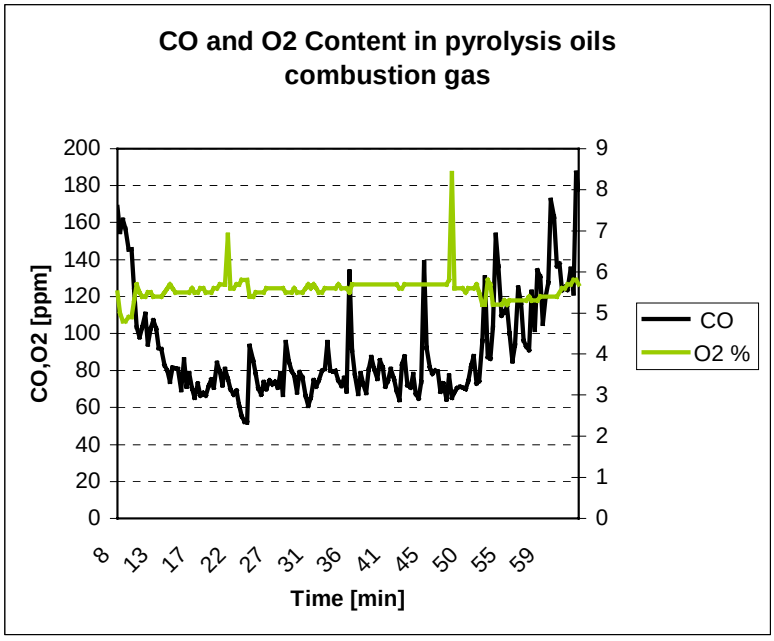

Figure 2.15. Typical CO emissions combusting forestry residue liquid

The experience with 10% and 30% pyrolysis liquid emulsions in light fuel oil clearly indicated that these could be ignited and cleanly combusted in very small burners and boilers normally used in single family homes of the size range of 20 kW. There were no problems with nozzles or valves during the combustion trials but it was found that the normal oil pump corroded and seized after a few days of operation. Separate pump tests were conducted where the emulsion was circulated and found that after 100-150 cycles the pump seized. Upon opening there was significant corrosion of the materials.

The main results of the combustion tests and comparison to other fuels are shown in Table 2.7. These results are from the combustion of liquids from a wide variety of sources over the years. The main factors that have varied are: solids from 0.1 to 0.7 wt%, water content and therefore viscosity and heating value. Since there is yet no specification for pyrolysis liquids and no commercial production and no commercially available burners or engines, the quality requirement is not known. Both particulate and NOx emissions are higher than for light fuel oils. NOx has an important contribution from fuel nitrogen and particulates from ash and solids in the fuel. NOx emissions were higher for the forestry residue fuel due to a higher fuel nitrogen content. Carbon monoxide (CO) emissions are a good indication of how well the fuel is combusting.

Table 2.7. Pyrolysis liquid properties, emissions and comparison to other fuels

		Medium light fuel oil	Fast pyrolysis liquid	Wood chips	Heavy fuel oil
Viscosity cSt	30 °C	9	300....100		600
	50 °C	4	70...10		180
Solids		-	0.7 … 0.01		<0.05
Ash wt%		<0.010	0.1...0.01	2...4	0.03
Sulfur wt%		0.15	0	0	1
Nitrogen wt%		0	0.03....0.1	0.1...0.2	0.3
Typical emissions					
CO (ppm)		15-30	30-100	500-6000	5-30
NOx (ppm)		80-120	120-180	80-160	200-400
particulates(Bach.)		0.2 - 1	2 - 5	+tars, PAH	1-4
g/Nm3			50-100	100-200	50-200

2.2.8 Engine tests (task 7)

The objective is to support the development of a BFO as power plant engine fuel by generating basic engine performance and emission data. The specific objectives of the task were:

- The description of spray injection, formation and ignition;
- Evaluation of engine performance;
- The analysis of emissions of an engine fueled with BFO;
- Study of residuals in the combustion chamber.

The proposed work was innovative in the following points:

- Use of high-speed visualization techniques to characterize the behavior of commercial Diesel engine injectors with BFO;
- A systematic investigation of the performance of a commercial DI Diesel engine fueled with BFO.

The values of the break-up length and the cone angle with the single orifice nozzle were always smaller for BFO, if compared to Diesel fuel. The same trend was observed with the four-hole nozzle. In this case, in order to visualize the sprays exiting from the nozzle, a white shield was placed just behind the nozzle tip: this optical arrangement determined the simultaneous visualization of the spray and of its shadow on the underlying screen.

Fully developed spray patterns for Diesel and BFO fuels were compared on a larger field of view. The BFO spray is characterized by a good degree of atomization as evidenced by the strong similarity with diesel fuel sprays. However, Diesel fuel spray shows a wider cone angle and greater break-up length; this can be arguably attributed to the higher value of BFO viscosity respect to diesel fuel (more than one order of magnitude).

During the visualization tests, no wear or clogging of the injector was recorded. Anyway, an endurance test was specifically performed on the pump-injector system, in order to check the system in the long run. The 4-holes injector was used. After a total running time of 26 minutes at 1500 rpm, the joint between the electric motor and the PF-type pump failed. The pump was disassembled, revealing no trace of wearing in the plunger-barrel assembly, nor in the delivery valve. The joint failure was apparently due to an increased resistance offered by the pump, to be likely attributed to an overheating of the driving cam. No clear indications exist that the inconvenience must be attributed to the use of BFO. No major obstacles could therefore be anticipated to the tests on the engine: the fuel delivery system resulted suited to the direct use of BFO, showing no trace of abnormal degradation and hence no need for modifications.

In the engine tests, the cylinder pressure for blends with an increasing percentage in BFO are reported. Steady running was recorded for periods of nearly an hour. 37.5% (in volume) was the maximum amount of BFO allowing for a stable operation. Typical rate of heat release for 12.5%, 25% and 37.5% BFO blends in Diglyme are shown in Figure 2.16. If compared to the Diesel behavior, they show a steeper rise and a slightly narrower peak of premixed combustion, followed by a diffusive phase, which gets more marked as long as the amount of BFO decreases. Cylinder pressure data for two different BFO-emulsions (prepared from BFO produced by Dynamotive and VTT) is also reported. Both curves present a typical shape characterized by an abrupt increase of the pressure and a higher peak, coherent with the poorer self-ignition properties of the emulsions. This is confirmed by the much longer ignition delays, as inferred from the needle lift data. The rate of heat release better allows to appreciate the sudden, essentially premixed combustion, particularly evident in the case of Dynamotive-Diesel emulsions.

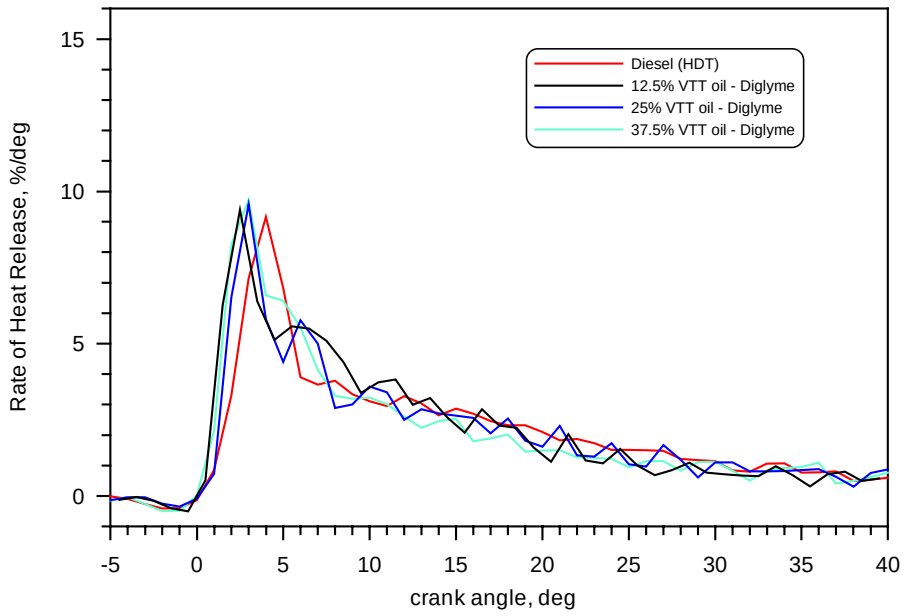

Figure 2.16. Heat release rate for BFO-Diglyme blends and Diesel fuel

The specific fuel consumption, in g/kWh is reported. The obtained results are scaled with the different Heating Value of the base compounds: the amount of fuel necessary to deliver the same power output with BFO-Diglyme blends got larger increasing the percentage of BFO. The two BFO-Diesel emulsions present a different value of consumption, even if the amount of BFO is the same: this effect must be likely ascribed to the different parent BFO.

The NOx emissions from the BFO-Diglyme mixtures were systematically lower than both the reference Diesel (HDT) and pure Diglyme, and their values seem to get lower, increasing the BFO amount. HC emissions are much lower than Diesel fuel, of the same order of magnitude than pure Diglyme: increasing the BFO beyond 25%, the HC emissions rise, suggesting there is a trade-off between chemical and physical effects: the atomization characteristics become probably less suitable for an effective combustion. The CO emissions are noticeably higher than those of pure Diglyme and of the same order of magnitude of Diesel fuel: they decrease with the self-ignition characteristics, as expected. The results obtained with the two emulsions must be compared to those of Diesel fuel: while the HC level is similar, the Dynamotive Oil-based emulsion show a very high peak of NOx emissions, coherent with the peculiar combustion behavior, as evidenced by the rate of heat release.

The ignition delay was evaluated as the time lag between the start of the needle lift and the start of combustion (inferred from the heat release data). The ignition delay increases with the BFO concentration in Diglyme blends. The two emulsions show an even longer delay. By means of a Reference Fuel Correlation, previously obtained, the Cetane Number was evaluated from the Ignition Delay. Reporting the CN as a function of the BFO concentration in BFO-Diglyme blends, a trend can be estimated, allowing evaluating the CN number of pure BFO. Its value turns out being about -10.

Note that the Cetane Number is a conventional way to characterize the ignition quality of a diesel fuel. The CN scale is defined through blends of two reference fuels, Cetane and heptamethylnonane, having CN of 100 and 15 respectively. Some fuels can exhibit an auto-ignition quality even better than pure Cetane. An example are some oxygenates, as their CN is greater than 100. This is to emphasise that the CN scale has no strictly physical meaning. BFO has a negative (or zero) value, which has the following meaning:

a) It is an indication of extremely poor auto-ignition quality (as opposed to some literature references): as a pure fuel, it should not self-ignite in a series Diesel fuel.

b) The suggested value was obtained by extrapolation from a series of blends with increasing content of BFO: the so-called 'blending method'.

c) Being obtained this way, this CN value can find its use in the evaluation of the CN of a blend (or emulsion), as the weighed average of the components' CN. As a matter of fact, IM used it to independently check the CN of BFO-Diesel emulsions with good agreement to CANMET specs.

Engine durability can seriously impair BFO application. Special attention was paid to the fuel delivery components, as their degradation is likely to have consequences on the performance and the emissions. Typically no decrease in performance was appreciated during each run (lasting ~1 hour), nevertheless the injector was always took down for inspection, at the end of each test. The needle was always within tolerance, some darkening in color being occasionally noticed; injector blocking was recorded only with 50% (vol.) BFO blend.

Some deposit build-up on the outer nozzle tip was observed after running the engine with BFO-Diglyme blends. Apart from the build-up of residuals on the outer surface, the injector was still functional. After an attempt to run on a 50% blend, the needle was sealed in its seat and two of the four holes were blocked. This inconvenience was practically absent with micro-emulsions of BFO in No. 2 Diesel.

The engine head and the fuel pump were thoroughly inspected at the end of the whole series of tests (extending over several running hours). Both the cylinder wall and the piston top were in good conditions, traces of BFO residuals being located on the exhaust valve seat. The plunger and ducts of fuel pump were functional, with no trace of erosion or corrosion.

2.2.9 Market opportunities for bio fuel oil (task 8)

The objective is to determine the competitiveness of BFO as heating oil in Finland and Sweden.

The main markets for BFO are either as a light fuel oil (LFO) or heavy fuel oil (HFO) replacement. LFO is use almost exclusively for heating due its' high price whereas HFO is used both for heating purposes and as a fuel for combined heat and power applications. Other applications such as co-firing with other fuels in power boilers is also technically possible, but it is believed that solid biomass will be used here.

The price of LFO and HFO in selected European countries is show in Fig. 2-14. And as can be seen in Figure 2.17, the non-taxed price for LFO is for the most part 50% higher than for HFO. In addition, depending on the country, taxes on LFO tend to much higher. This gives added incentive to develop solutions for the combustion of pyrolysis liquid at a smaller scale than that of heavy fuel oils. Thus the intermediate size boiler range for the studies at Fortum has been chosen.

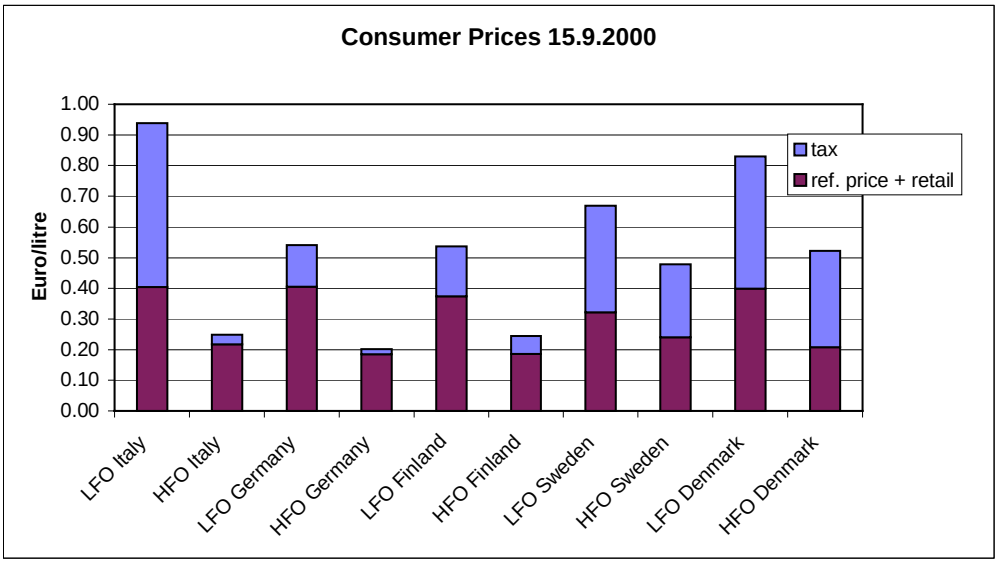

Figure 2.17. Consumer price of heating fuels in selected European countries

The effect of the fluctuation in crude oil prices is shown in Figure 2.18 on LFO (gas oil) and LSHFO (low sulphur heavy fuel oil). One can see a tripling in the international market prices for LFO and HFO over the past 2 years. These increase in prices illustrate the vulnerability European countries are to the effect of crude oil prices and give added incentive to search for solutions for alternatives.

Unfortunately these fluctuations also illustrate the problems in developing alternatives to crude oil based products since the profitability in making investments in alternative energy technologies can greatly vary if the selling price of the alternative is tied to the price of petroleum products

Based on the market analysis presented here, it is obvious that the replacement of light fuel oils will give more economic incentives.

In addition, there will be increased demand for these renewable energy products due to various government incentive programmes which will assist in market introduction by a combination of tax credits on the fuel, investment assistance for BFO production and use.

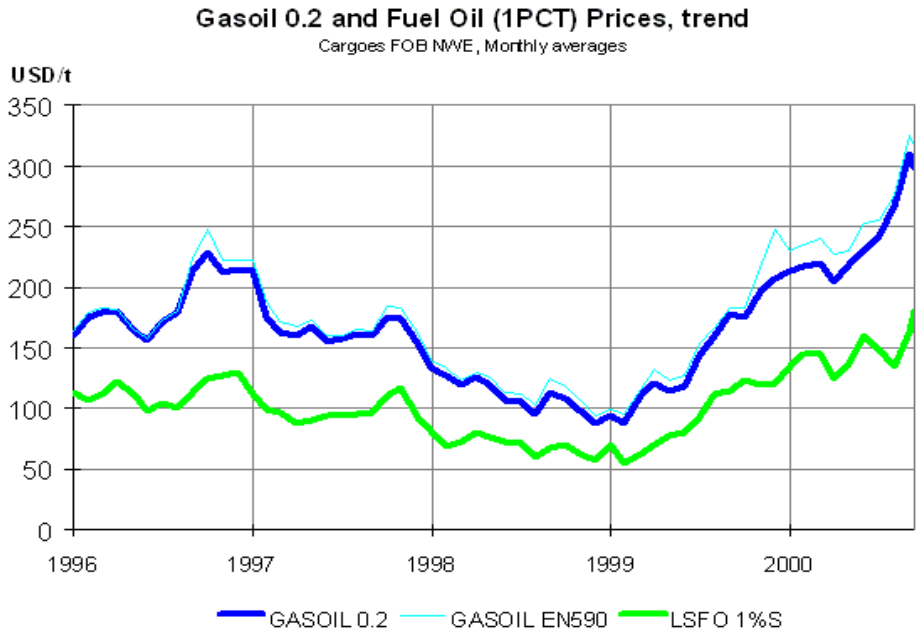

Figure 2.18. Market prices for LFO (gas oil) and low sulphur HFO (LSHFO)

The adverse properties of BFO as fuel are well known. Hot vapour filtration (HVF) has been identified as one alternative to improve BFO fuel quality. Product cost/value ratio is defined to study improvement of BFO quality. In effect this ratio expresses, how many times more expensive BFO is to commercial alternives.

Using the current assumptions about performance of BFO production (a "generic" pyrolysis), BFO replacing heavy fuel oil (HFO) would be 1.6 to 1.8 times more expensive than HFO in Skandinavia. A hot filtered BFO would be about 1.1 to 1.4 times more expensive than light fuel oil (LFO), Figure 2.19. Therefore it is concluded that HVF, if technically feasible, would improve the competitiveness of BFO. It may also be seen that because of different feedstock and fuel oil cost, the competitiveness of HVF appears different in these two countries.

Further improvements through the integration of pyrolysis to a boiler plant have been estimated to lower BFO production cost further.

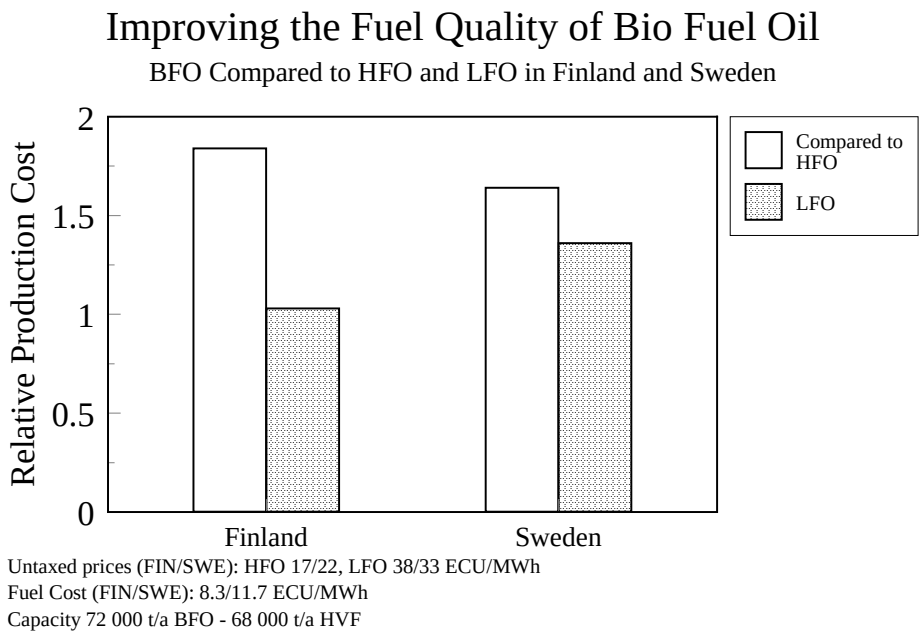

Figure 2.19. Product cost/value ratio in Finland and Sweden. Fuel oil prices as of September 15, 2000.

3. CONCLUSIONS

3.1 APPLICATIONS

The work aims in developing two applications for a new liquid fuel, bio fuel oil (BFO), or pyrolysis liquid. The two principal applications are BFO use as a boiler fuel and BFO use as a diesel engine power plant fuel.

Replacing of both heavy and light fuel oils in boilers is considered, although it is likely that the first alternative is only applicable in some rare circumstances. Replacing LFO in heating is emphasised, as this application may be feasible in medium term (within approximately 2-3 years). Experimental work in full-scale boilers was performed. Using BFO as power plant fuel is technically less developed. Therefore valuable basic data concerning use of BFO in engine power plants was generated. It is believed that the engine application will take longer to commercialise than the boiler application.

Only energy uses of BFO are considered in this project. Although other applications (for example, feedstock for the production of chemicals) exist, it is believed that these are usually quite case specific.

3.2 TASKS

3.2.1 Task 1

Hot vapour filtration is very efficient method to remove particles from the pyrolysis vapours and to improve the quality of the product liquid. However, the successful implementation of the filtration requires optimised filtration conditions.

The most critical parameters are filtration temperature, face velocity and particulate loading. The particle size distribution also plays important role in successful design of the filtration process. When filtration conditions are favourable a good filtration performance can be met. This includes not only the efficient particulate removal but also efficient detachment of dust cake from the filter surfaces by high pressure pulsing and discharging the dust from filter vessel. Hot vapour filtration of pyrolysis vapours was demonstrated successfully in PDU scale.

3.2.2 Task 2

Bio-oils in diesel emulsion fuels were produced and their stability investigated. Results were analyzed using a statistical model. A quadratic response surface model agrees well with experimental results. Dominant parameters are bio-oil and surfactant concentrations and power input, and there are optimal loci for different bio-oil concentrations that minimize the final costs of emulsified products.

Fuel properties such as cetane number, viscosity and corrosion were characterized. Ensyn pyrolytic oil had a cetane number of 20.6±1.3. Usually it is not easy to determine the cetane number of pyrolytic bio-oil due to its poor combustion characteristics. However, when emulsions were formed it was possible to do so by linear interpolation. The viscosity of emulsified fuels was best described by Einstein's equation for dilute solid dispersions.

3.2.3 Task 3

All the objectives of the task were met. Total of 5.8 tonnes of pyrolysis liquid was produced for utilisation tests and quality improvement work. It was found that a relatively high reaction temperature of 530 °C produced the highest liquid yield in the PDU unit, when forest residue fuel was used as feedstock. In the bench scale unit the maximum liquid yield for straw was around 480 °C. The residence time was not varied. A shorter residence time than the present 2 seconds in the PDU might have been more favourable. However, it could not be shortened because of excessive carry over of fines to the liquid, if reactor gas velocity would have further been increased. The organic liquid yield was 66 wt%, when a dry (2 wt% moisture) pine feed was used. Finally, the unit PDU unit was operated successfully in a steady-state mode to enable hot filter operation.

3.2.4 Task 4

Materials. Because of acidity (pH 2-3) of pyrolysis liquids following recommendations for materials are suggested:

- Plastics or AISI 316 for storage
- Plastics, copper and its alloys (no abrasion), AISI 316 for piping applications
- AISI 316 or better acid-resistant steel for process equipment

Due to **instability and reactivity** of pyrolysis liquids following storage conditions are recommended:

- Air-free plastic or stainless steel containers
- Storage temperature 15 °C, but at least below 25 °C
- Constant slow propeller stirring

Following is recommended for **handling**:

- Air should be avoided
- Heating above 60 °C should be avoided
- Heating between 40-60 °C should be minimised to a few hours
- Hot surfaces has to be avoided

For **poor-quality pyrolysis liquids** following is suggested:

- Homogenising of the liquid with simultaneous addition of 5-10 wt-% methanol. A 1-2 wt-% addition of formic acid for homogenisation is not adequate.
- Slow constant propeller-type mixing provided during the storage.

3.2.5 Task 5

The combustion fundamentals of BFO and BFO derived fuels (emulsions and mixture) were characterised at both normal and high-pressure conditions and the peculiar features identified. Two single-droplet combustion chambers were developed and a maximum pressure of 60 bar was reached. Droplets were suspended to a thermocouple or to a quartz fibre. The thermal behaviour exhibited by droplets was followed by means of high-speed digital shadowgraphy.

A database relative to heating, swelling, vaporisation, liquid burning, cenosphere formation and burning processes was formed and all the relevant parameters were recognised and correlated with the fuels properties.

The main results obtained in the Task activity are summarised in the following.

- All the fuels were easy to ignite at normal and high pressure.
- The swelling phenomenon reduced its intensity with pressure: it completely disappeared at pressures higher than 10 and 20 bar for emulsions/mixture fuels and pure pyrolysis oil, respectively.
- The diameter of emulsion and mixtures droplet decreased during burning with a D^2 law.
- The liquid burning rate was around 1 mm^2/sec at normal pressure, increased to about 1.5 mm^2/sec at 12 bar and to 2 mm^2/sec at 45 bar very similarly to commercial light diesel oil.
- Mixture and emulsions formed carbonaceous residual at different extent and with different morphology and internal structure. This influenced the solid burning rate. The dominant parameters in the formation of solid residuals were the oil quality, the environment pressure, and the thermal level achieved by droplets before cenosphere formation.

The most significant result has been the observation that one of the emulsions, the emulsion composed by 30% of hot filtered pine oil in #2 Diesel oil, gave no carbonaceous residuals in all the conditions tested. Moreover, this emulsion exhibited a general behaviour very similar to a commercial diesel oil. These two observations demonstrate that a cautious combination of oil quality and fuel technologies could open the way for an immediate and successful utilisation of BFO in furnaces and Diesel engines.

3.2.6 Task 6

Based on earlier and the current boiler combustion tests it is concluded that BFO can be effectively combusted using properly modified simple and relatively inexpensive pressure atomisation equipment and emissions reduced to acceptable levels with a combination of optimisation of combustion conditions and good quality fuels. The major modifications that were employed within this work to existing commercial equipment was an acid resistant pump, an oil preheater with low surface temperatures, a refractory lined pre-chamber between the burner and boiler, air operated valves and a computer based control system. These were found to be required in order to optimize combustion conditions and to pump and atomize

this fuel. These modifications would increase the cost of a typical system by about 50% and would not be practical in a commercial system. These modifications can though be used by a burner manufacturer to build a platform for a prototype system that could be used for field trials.

From both a viscosity standpoint and a solids standpoint, both the forestry residue and pine sawdust fuels produced by VTT Energy were of sufficiently good quality to be combusted cleanly in light fuel oil boilers. The only notable emissions that are higher than for light fuel oils is that of particulates and tars. It is believed that once a burner is designed specifically for pyrolysis liquids, it will be possible to reduce futher these emissions and combust these fuels cleanly in this size class.

The experience with 10% and 30% pyrolysis liquid emulsions in light fuel oil clearly indicated that these could be ignited and cleanly combusted in small burners and boilers normally used in single family homes of the size range of 20 kW. It was therefore concluded that a new, acid resistant pump would be needed for the emulsions. This pump development was not included in the original work plan and will require further investigations. It is further believed that long term tests will show that the normal in-line oil preheater with surface temperatures of 120-150 C will also need to be replaced with emulsions due to slow tarring of the surfaces.

3.2.7 Task 7

The performance of a commercial DI Diesel injection system with Bio Fuel Oil was characterized by means of high-speed imaging. The BFO spray was injected in a transparent test rig, and its time evolution visualized with back illumination: this allowed appreciating the extension of the liquid part of the spray, as well as some characteristic parameters. BFO spray showed good atomization quality, even if the break-up length and the cone angle were smaller than Diesel fuel. These effects, likely due to the greater viscosity of BFO, were observed both with a single-hole and with a four-hole injector.

The injection tests confirmed the possibility of using a standard Diesel fuel supply system with BFO, as the performance and the efficiency weren't substantially impaired.

In order to assess the current limitations to the use of BFO in a light-duty D.I. Diesel engine, a series of tests were carried out with a stock single-cylinder, without any modification and/or pre-treatment of the fuel. The physical-chemical properties of Bio Fuel Oil, which would preclude its direct application in a production Diesel engine, were smoothed by blending it with Diglyme. Blends with increasing percentage of BFO in Diglyme were tested, together with two different micro-emulsions of BFO in No.2 Diesel fuel. The main results can be summarized as follows.

- Reliable operation was recorded with BFO-Diglyme blends, with a BFO content up to 37.5% in volume. Micro-emulsions of BFO in No.2 Diesel exhibited a peculiar combustion behavior, with a sharp peak of heat release rate.
- Much lower HC and NOx levels than Diesel fuel characterized BFO-Diglyme blends, CO levels being comparable. The emission profile of micro-emulsions didn’t feature

appreciable deviation from Diesel fuel, other than the peak of NOx recorded with the Dynamotive oil emulsion.

- The fuel consumption scaled with the heating value of the samples, being higher for BFO-Diglyme blends.
- Ignition Delays of BFO-Diglyme blends increased with the BFO content. Using a Reference Fuel Correlation, the cetane number of pure BFO was estimated by means of the blending method.
- The critical components of the engine experienced no relevant trouble, after several running hours.

3.2.8 Task 8

The international market prices for LFO and HFO have tripled over the past 2 years. These increase in prices illustrate the vulnerability European countries are to the effect of crude oil prices and give added incentive to search for solutions for alternatives.

Unfortunately these fluctuations also illustrate the problems in developing alternatives to crude oil based products since the profitability in making investments in alternative energy technologies can greatly vary if the selling price of the alternative is tied to the price of petroleum products.

Based on the market analysis presented here, it is obvious that the replacement of light fuel oils will give more economic incentives.

In addition, there will be increased demand for these renewable energy products due to various government incentive programmes which will assist in market introduction by a combination of tax credits on the fuel, investment assistance for BFO production and use.

4. EXPLOITATION

Implementation in its' broadest sense refers to commercial exploitation and in the case of pyrolysis liquids for fuels, this has not yet happened. The technology, depending on the application, is at the demonstration stage where a number of pilot plants are producing liquids in order to further develop applications. Developers of pyrolysis technologies who have been continually attempting to demonstrate their technology for the past ten years but have not yet been successful in scaling up to this scale. Therefore the only implementation that this project could possibly contribute to is the demonstration of specific solutions to parts of the overall fuel chain. Here it is also important to differentiate between what is technically feasible and what is economically feasible. Since the VTT PDU unit that was used in this project to produce the liquid samples and since the cost of emulsions that were produced is not known, comments referring to implementation or exploitation here are more of a technical nature.

Hot filtration of pyrolysis vapors is ready for scale-up and longer-term tests. Obviously the technology can only be exploited integrated to a pyrolyser, and therefore the utilization of this process may only be done as part of an overall development effort. Preparation of emulsions from BFO requires also further R&D before exploitation. Basic combustion tests and tests in a single-cylinder engine revealed interesting interactions between mixtures and emulsions of BFO, and points out towards new research topics. The work carried out was novel, and in addition to demonstration efforts of BFO combustion, the results will be useful also in related scientific research projects.

In the use of BFO in medium size boilers, the work has shown that there are no major problems with igniting and combusting pyrolysis liquids produced used in this project. The samples from pine sawdust with low solids and low moisture (<25%) content gave a more stable flame than the products from forestry residues that had high moisture content (30%). The main concerns are in long-term durability of combustion components, in tar and particulate emissions, and in tar and char deposits in the burner retention head, nozzles, valves and pumps. There also remain questions regarding long-term storage and mixing of liquids with changes in fuel properties. In the case of pyrolysis / mineral oil emulsions, combustion of these was successful in smaller boilers than the pure pyrolysis liquid. Here it was however noted that the normal pump used with these burners was corroded and would have to be replaced with a more suitable pump.

Therefore in order to implement and exploit the results of this study, a cooperation project with a burner manufacturer must be initiated in which the technical solutions to these areas is assessed and appropriate technologies developed and constructed. Since there is not yet any production in Scandinavia, there is currently little incentive by burner manufacturers to develop these burners. The implementation of this work will therefore require that the pyrolysis liquid manufacturers work together with burner manufacturers.

5. PHOTOGRAPH

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