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VTT TIEDOTTEITA

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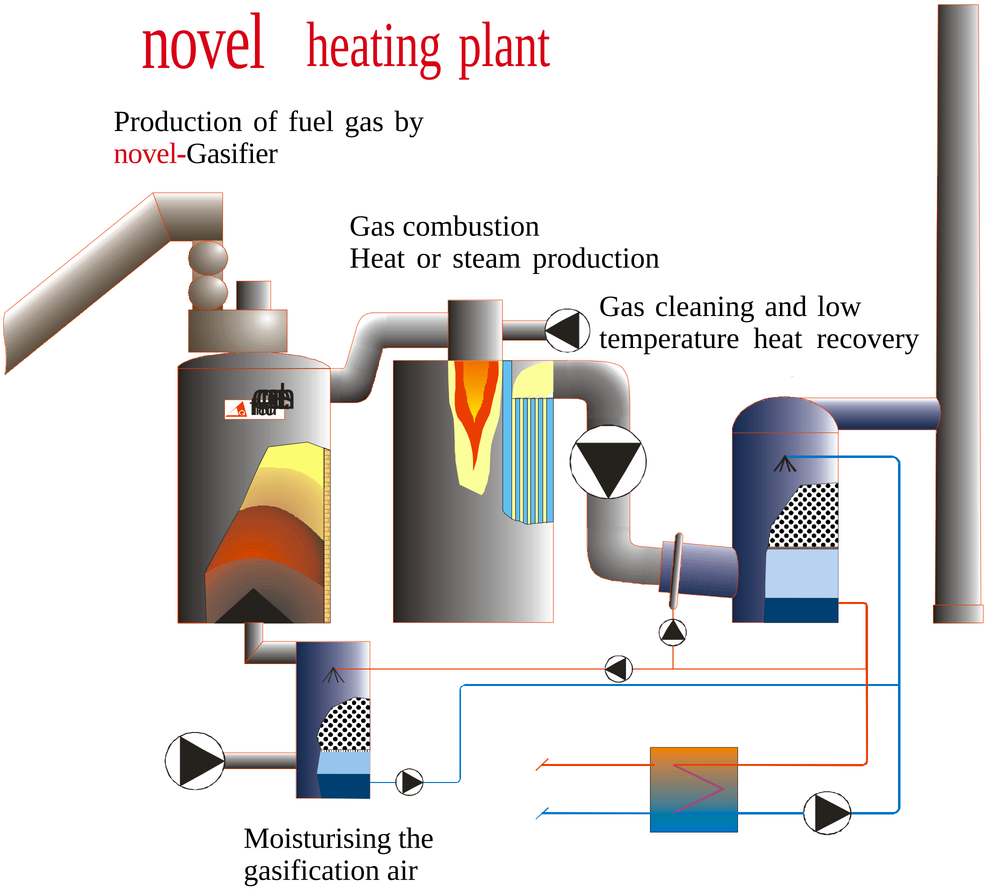

TECHNICAL RESEARCH CENTRE OF FINLAND

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Abstract

The project concerned three different approaches to achieve reliable operation in fixed-bed gasification of available biomass residues. The first approach was based on the pre-treatment of fuels so that they can be used in standard downdraft gasifiers. The second approach was based on using commercially available updraft fixed-bed gasifier for heating applications. The third and most challenging approach of the project was based on the development of a new type of gasifier, which is independent of the natural descending fuel flow caused by gravity. The project was realised in October 1997 - September 1999.

The downdraft gasification tests were carried out in Italy in a Martezo 100 kVA gasifier-engine-generator facility. Test runs with a range of Italian biofuels were carried out to a) create criteria for fuel selection, b) collect reliable performance data with suitable fuels, and c) identify technical possibilities for broadening the feedstock basis of this standard downdraft gasifier by using mixture fuels and additives to avoid ash sintering. The test results and experiences clearly demonstrated the limitations of this type of commercial gasification technology. The classical downdraft gasifier can only be operated with very high-quality sized feedstocks such as wood blocks (5 - 10 cm in size) and wood briquettes. Even with the ideal fuels, the operation was rather unstable and also some tars were produced. When a mixture of 50% wood blocks and 50% robinia chips was tested, severe channelling problems were met and it was impossible to reach stable operation.

Operation experiences from nine commercial updraft gasifiers operating in Finland and Sweden since the mid-1980s were collected and evaluated. These updraft gasifiers operate well with sod peat and wood chips, and the availability of Bioneer plants has been very high. Test results obtained in the project for one of the commercial Bioneer plants with chipped Italian coppice wood were also very good. However, these gasifiers cannot be reliably operated with low-bulk density fibrous fuels such as bark, saw dust and shavings, which do not flow down in the reactor without channelling problems.

The third technical approach of the project was realised by designing, constructing and testing a 300 kW_{th} pilot plant for a new-type of gasifier, which is based on forced fuel

flow and is also suitable for low-bulk-density fibrous biomass fuels, which cannot be used in standard fixed-bed gasifiers without expensive fuel pretreatment. The pilot plant was connected to a secondary catalytic gas cleaning device, which made it possible to produce tar-free product gas suitable to engine use. The development of a new fixed-bed gasifier will make it possible to effectively utilise such biomass residues and energy crops that cannot without expensive pretreatment be used in the presently available fixed-bed gasifiers. Examples of these low-bulk density feedstocks are forest residue chips, saw dust and crushed bark, which all were successfully tested in the project. The development of an effective catalytic gas cleaning method for the novel fixed-bed gasifier made the small-scale gasifier-engine power plant technically available also for other biomass fuels than the dried low-ash wood lumps used in present downdraft gasifiers. However, further activities are required to demonstrate the whole gasifier, gas cleaning and engine concept and to define the life time and availability of the catalytic gas cleaning system.

Preface

The work was carried out in co-operation between the following partners: VTT Energy and Condens Oy, Finland and Finesport Engineering and Antiche Terre soc. coop.r.l, Italy. VTT Energy co-ordinated the project. The project was carried out during the period of 1 October 1997 - 30 September 1999. The contact information about the partners is presented below.

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Espoo, September 2000

Authors

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1. Objectives of the project

The project was related to small-scale (< 10 MW_{th}) power and heat production from biomass residues. The overall aim was to define the requirements for reliable and successful operation in three different types of fixed-bed gasifiers. The specific objectives of the project were

- to define the requirements for the feedstock quality needed to guarantee reliable operation with respect to fuel flow, pressure drop, ash-sintering and tar formation in an existing commercial downdraft gasifier.
- to collect operation experience from the commercial Bioneer updraft gasifiers
- to develop and test a new type of fixed-bed gasifier design, which is based on forced fuel flow and consequently allows the use of low-bulk-density fuels.
- to develop and test on the pilot scale a simple and reliable secondary catalytic reactor required for the complete decomposition of tars.
- to evaluate the economic feasibility of different fixed-bed gasification systems

2. Technical description

The project comprised five tasks, the results of which are presented in this chapter.

2.1 Laboratory tests

2.1.1 Characterisation of Italian biomass fuels

In this task VTT carried out laboratory fuel characterisation tests. The aim of the work was to support the development and testing work of the other tasks. One of the key issues in utilising agricultural residues, wood wastes and short-rotation forestry species in high-temperature combustion or gasification processes is the ash behaviour. The ash content and its composition are the most important variables in determining the possible operating conditions as well as the reactivity of different biomass fuels.

Finesport collected representative samples of ten local potential fuels from the Umbria area and submitted these samples to VTT in early 1998. All samples were firstly analysed for their particle size, bulk density and proximate and ultimate composition. In addition, the alkali metal and chlorine contents were determined both directly for the feedstock (by neutron activation analysis) and for the ashed samples (by XRF). Data for these analyses are presented in Table 1.

Feedstocks W1, W2 and W3 were waste products from local wood processing, furniture and carpentry industries. W1 and W3 were in the form of fine sawdust and would require densification either by pelletising or briquetting. The ash content of W3 was rather high and it also contained traces of paints and/or other coating materials. F1, V1, O1 and R1 were chipped from harvesting residues. F1 was coppice wood made from small trees and bushes, O1 and V1 were local residues of olive and wine trees and R1 consisted of robinia chips. P1 and P2 were straws of wheat and barley, respectively, and they were in loose form. The dehydrated sludge (RM1) had a very high sulphur, nitrogen and ash content and also contained rather much heavy metals. Consequently, the use of this contaminated fuel would require special gas cleaning methods, which were not the focus of this project. Consequently, no further work was carried out with the sludge feedstock.

As the second step of the characterisation work, the ash and reactivity behaviour was determined in a thermobalance. Methods similar to those described in a previous publication [1] were used. The combined gasification reactivity and ash sintering behaviour was determined for the samples, olive tree (O1), wine (V1) and robinia (R1). These fuels were considered as potential candidates for the tests in tasks B - C. On the other hand, the gasification and ash behaviour of these fuels had not been previously studied at VTT. Both straws (wheat and barley) contained so much alkalis and chlorine and had as a low bulk density (abt. 50 kg/m^3) that, according to previous VTT experience, they cannot be considered as potential fuels for fixed bed gasifiers without additives and densification.

The thermobalance tests were carried out in two conditions: 1) 850 °C and 1 bar (100%) steam (reference) and 2) 850 °C 0.5 bar air + 0.5 bar steam (50%/50%). After the tests, the physical structures of the ash residues were investigated under a microscope. The results are shown in Figure 1. The results of the thermobalance tests are shown as graphs of instantaneous reaction rate (i.e. mass rate against residual ash-free mass) *versus* fuel conversion (i.e. including pyrolysis).

All the samples had a very high reactivity in the conditions measured. In general, only slight ash sintering was detected in all the tests. For robinia, no ash sintering was detected in the air-steam test. Due to the high reactivity these fuels would be fairly suitable for fluidised-bed gasification processes.

The classical downdraft gasifiers are usually operated at peak temperatures of the order of 1 000 - 1 400 ^{o}C in the throat, and only low-ash (<1%) clean wood fuels or fuels with very high ash melting temperatures can be used without ash sintering problems. Only the tropical hard wood waste (from furniture industry) was close to meet these requirements. All other fuels contained too much ash and did not meet the particle size requirements.

The commercially available updraft fixed-bed gasifier of Task C is not as sensitive for the fuel quality and consequently, the following feedstocks were considered to be potential candidates for this process (without further pretreatment): W2, F1, O1, V1 and R1. In an updraft gasifier, the temperature of the hottest combustion zone is controlled by adding steam into the gasification air. As a result, the reactor is not as sensitive to ash sintering as downdraft gasifiers. However, if very much steam is needed the overall efficiency is reduced, in spite of the fact that steam addition is accomplished by humidifying preheated air in a special device, which takes the needed heat from flue gases. Thus, the ash behaviour is an important parameter also in updraft gasifiers when selecting an optimum level of air humidifying.

Table 1. Analyses for the selected potential Italian feedstocks.

	W1	W2	W3	F1	O1	V1	R1	P1	P2	RM1
	Europ. beech sawdust	Tropic. hardwood (pieces)	Pine wood waste dust	Broad leaves chips	Olive tree chips	Wine tree chips	Robinia chips	Wheat straw	Barley straw	Dehydr. sludge briquette
Moisture content, wt%	55.7	8.2	8.0	37.6	35.4	44.2	13.2	12.1	13.8	13.7
Proximate analysis, wt% d.b.										
Volatile matter	76.3	74.7	76.3	78.7	78.1	76.6	80.6	73.6	75.0	64.2
Fixed carbon	22.3	23.5	18.1	18.9	18.9	20.7	17.3	18.5	19.3	9.7
Ash	1.4	1.8	5.6	2.4	3.0	2.7	2.1	7.9	5.7	26.1
Ultimate analysis, wt% d.b.										
C	52.6	52.4	47.2	49.2	49.8	49.0	48.2	45.6	45.6	38.7
H	5.9	5.7	5.7	5.7	6.0	5.7	6.0	5.7	5.6	5.8
N	0.3	0.3	2.2	0.6	0.7	0.7	1.2	0.7	0.5	6.3
S	0.02	0.01	0.09	0.04	0.06	0.05	0.05	0.09	0.09	1.97
O (as difference)	39.8	39.8	39.2	42.1	40.4	41.8	42.4	40.0	42.5	21.1
Ash	1.4	1.8	5.6	2.4	3.0	2.7	2.1	7.9	5.7	26.1
LHV (d.b.), MJ/kg	19.9	19.6	18.0	18.3	19.0	18.3	18.2	16.8	17.1	15.7
Trace components, ppm-wt (d.b.)										
Cl	<50	<50	310	150	350	260	300	2 210	4 720	1 580
Na	150	60	1 260	100	290	190	140	710	1 470	2 590
K	1 910	3 380	1 570	2 830	8 710	9 430	3 140	16 200	16 700	2 360
Ash composition, g/kg ash										
SiO_2	10	0.6	17	4	6	2	1.2	55	36	12
Al_2O_3	1.7	0.1	4	1.4	1.9	0.6	0.4	0.5	1.2	19
Fe_2O_3	2.1	0.7	2.0	2.1	1.4	0.5	0.4	0.4	0.8	9
CaO	48	54	27	63	45	38	59	7	7	12
MgO	10	22	14	6	6	10	6	3	4	3
K_2O	12	19	3	13	27	36	18	23	28	1
Na_2O	1.4	0.5	4	0.8	1.3	1.0	1.0	2.0	5	2.2
TiO_2	0.1	-	17	0.1	0.1	-	-	0.04	0.1	1.6
SO_3	3	1	6	4	3	4	6	4	5	12
P_2O_5	5	1	1	5	7	7	7	3	4	12
XRF sum (normalised)	94	99	95	99	99	99	99	97	91	83

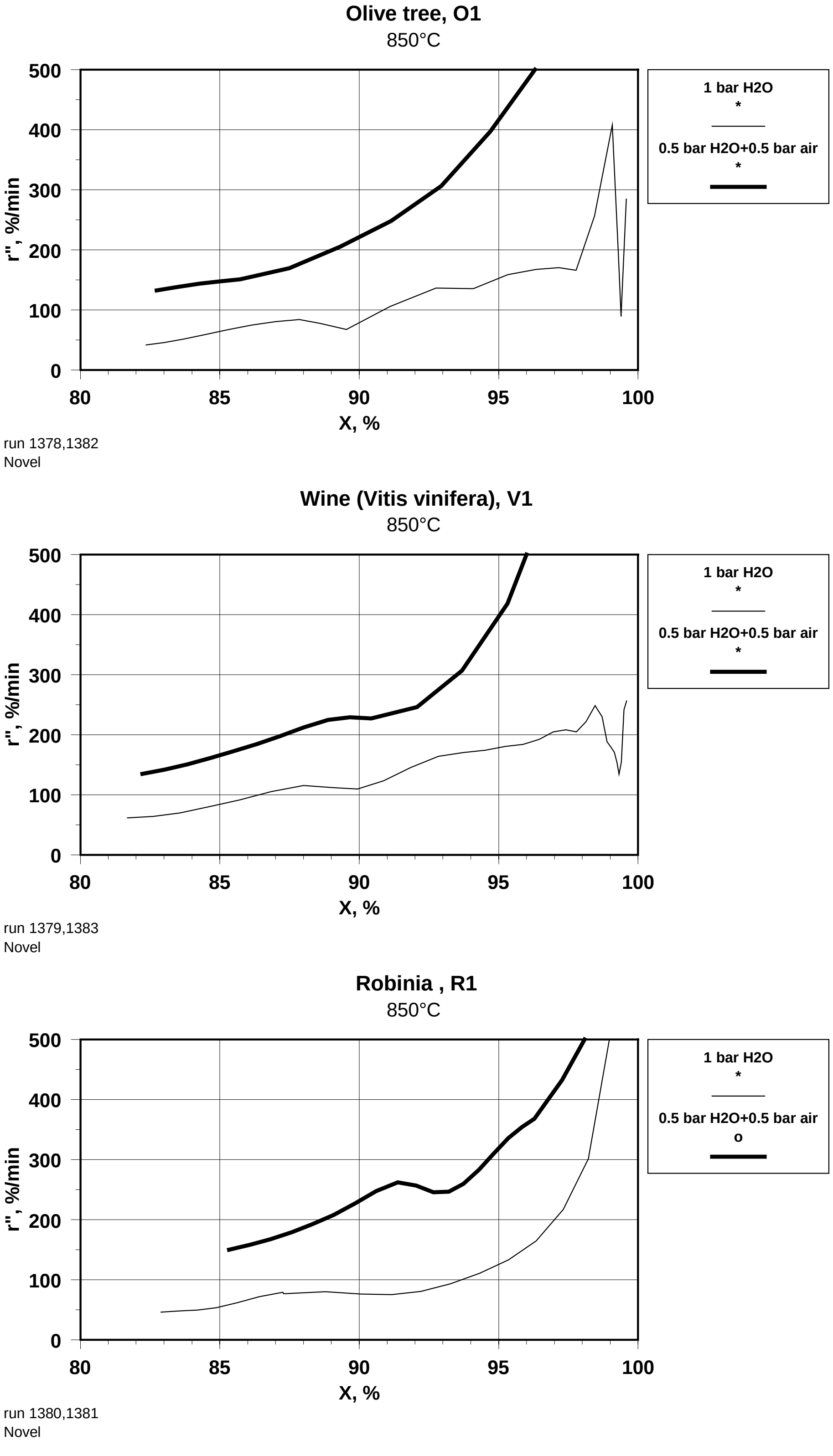


Figure 1. The reactivity and ash sintering behaviour of olive tree, wine and robinia. Degree of ash sintering: o *no sintering, * some sintering, ** partial but clear sintering (molten), *** complete sintering (molten).*

2.2 Test runs with the downdraft gasifier in Italy

2.2.1 Background and objectives

Downdraft gasifiers were originally designed for small-scale power production for engine use in transportation sector, water pumping and small stationary engine-generator plants. The standard type of downdraft gasifiers with a throat design (e.g. Imbert and Martezo gasifiers) has earlier been tested by several developers, and the following overall conclusions seem to be valid to well designed downdraft gasifiers:

- Stable and low-tar operation can be achieved with high-quality wood lumps and blocks that do not contain fines. The moisture content must be <20 - 25% and the ash content very low.
- There are fuel flow problems with low-bulk density fuels and with feedstocks containing fines. These problems result in increasing bed pressure drop, channelling and bridging problems as well as in occasional loss of char bed. These malfunctions also result in increased tar production.
- Tar-free operation can be achieved only with low ash fuels or with fuels having a very high ash sintering temperature, because peak temperatures of the order of 1 100 - 1 400 °C are typical of an ideal downdraft gasifier.

These generally accepted facts and previous VTT experiences from downdraft and updraft gasifiers with more realistic (or cheaper) wood fuels were taken as the starting point for the tests of this task. The aims were

- to study if the feedstock basis of a standard downdraft gasifier can be extended by using mixture fuels and additives to avoid ash sintering.
- to create a clear criteria for fuel selection and to collect reliable performance data with suitable fuels.
- to carry out detailed tar measurements in order to evaluate the operability of gasifier-engine sets based on this technology.

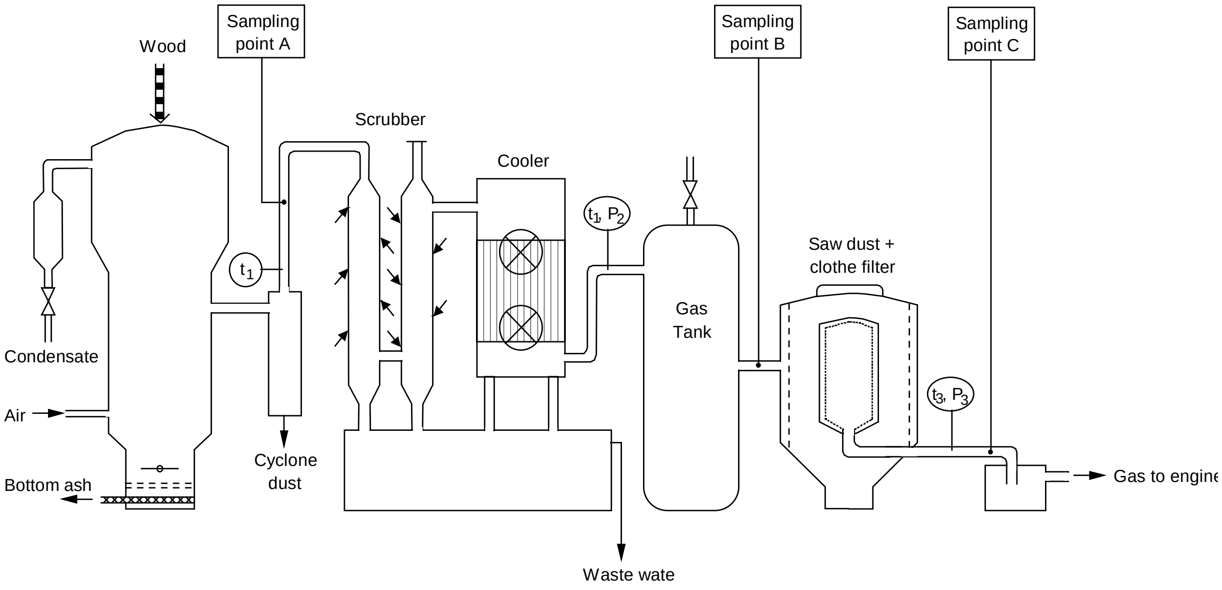
The tests were performed in two test campaigns. The first test campaign was carried in 1998 out using two so-called design wood fuels (low ash wood blocks), and the aim was to carry out detailed product gas and gas contaminant measurements with fuels that according to the gasifier manufacturer are suitable for this gasifier type. The second test campaign was carried out in 1999 with sawdust briquettes and with mixture of design wood and robinia wood chips.

2.2.2 Description of the test facility

Finesport and Antiche Terre carried out the downdraft gasification tests in the 100 kVA Martezo gasifier-engine-generator facility, located near the city of Perugia. The schematic diagram of the test facility is shown in Figure 2. The gasifier supplied by Martezo was of classical downdraft design.

The fuel was loaded before each test day into the gasifier, after which the airtight top flange was closed. The wood hopper was dimensioned to allow an 8 - 10 hour-operation at full load. The gasifier was operated at negative pressure. Gasification air entered into the central part of the reactor through several nozzles. Condensate was collected from the walls of the fuel hopper and was removed into a condensate tank. The hot central parts of the reactor were water-cooled, which produced warm water that was used for heating purposes or for supplying heat for fuel drying.

The product gas was led from the gasifier through a cyclone separator into a water scrubber. After that the gas went through an air-cooled gas cooler. The scrubbing water was circulated and the water level in the water tank was kept constant by removing the additional water released from the wood fuel. After the gas cooler the product gas was directed into a gas tank followed by a filter unit. Saw dust was used to remove residual tars from the gas and a cloth filter was used for final dust removal. Then the cleaned gas



Project: JOR3-CT97-0168
Partners: VTT Energy, Finesport, Antiche Terre, Condens
Test rig: Martezo downdraft gasifier, Perugia, Italy 1998

Figure 2. Schematic diagram of the downdraft gasifier-engine facility of Task B.

was led into the Mercedes engine. The engine was a naturally aspirating spark-ignited engine operating with wood gas alone. A start-up blower was used a few minutes after igniting the gasifier. After that the engine itself sucked the product gas. The engine was connected to a generator producing electricity, which was used for heating and boiling water in a large water tank. The capacity of the generator was controlled by changing the water level in the water tank. The system was controlled so that the engine speed and the voltage of the generator were kept constant. When the generator output was increased, the choke valve was automatically opened to increase the gas flow. The air to product gas ratio was automatically controlled in order to maintain good combustion.

2.2.3 Test results obtained with design wood fuels

Two different types of woody biomass feedstock were prepared for the first test campaign. Both feedstocks met the fuel requirements given by the gasifier manufacturer and were hence called "design fuels". The analyses of the test feedstocks are presented in Table 2.

Table 2. Analyses for the tested wood feedstocks.

	DW1	**DW2**
Moisture content, wt%	9.3	12.2
Ultimate analysis, wt% d.b.		
C	48.9	48.8
H	5.9	5.7
N	0.2	0.2
O (as difference)	45.0	45.3
Ash	0.3	1.2

DW1 = Design wood 1:

This fuel was of a high-grade residue from a sawmill and it was mainly composed of planks, which were cut to about 10 cm length. The typical particle size was 20 - 30 x 50 - 100 x 100 - 150 mm. The fuel was very dry and contained hardly any ash.

DW2 = Design wood 2:

This wood was made from young (5 - 10 cm thick) coppice wood by cutting to a maximum length of 10 cm. The larger wood stems were also chopped to 2 - 3 pieces. The typical particle size was in the range of 50 - 70 x 50 - 70 x 70 - 150 mm. The relatively thick bark of wood was not removed before making this chopped wood. Due to the high bark content, the wood contained somewhat more ash than the typical “design” wood materials of downdraft gasifiers [3].

Gas composition and process data

An example of the measured contents of the main gas components and gas temperature at point A (raw gas after the cyclone) as a function of operation time is presented in Appendix 1. The average gas compositions with their measured standard deviations in the different test runs are presented in Table 3.

The large variation in gas analysis clearly indicated that the gasifier did not operate as an ideal downdraft gasifier throughout the test days. During a stable operation period a glowing char bed, formed in the throat (measured temperature was 1 050 - 1 160 °C), decomposed almost all the tar compounds to gases. In addition, in gasification reactions, carbon and the gas components reacted, forming hydrogen and carbon monoxide. During these periods, very good gas was produced (typically 20 - 22% CO and 18% H_2). However, the bed evidently collapsed occasionally and channels were formed in the char bed. This resulted in poor gas composition (high CO_2 and low CO and H_2 contents), and more tar also penetrated through the hot zones of the reactor. After some time a new char bed was formed in the reactor and the performance of the gasifier improved again. Hence, it was typical of the operation of this gasifier with both test fuels that the gas composition varied in a rather large range. Similar results were obtained in the mid-1980s with a downdraft test gasifier of VTT operated with ordinary wood chips [4].

Table 3. Average gas composition (vol%) in the test runs.

Run	H_2		CO		CO_2		CH_4	
	mean	STDV	mean	STDV	mean	STDV	mean	STDV
13.5.	14.9	2.8	19.2	1.4	12.9	1.3	1.9	0.5
14.5.	17.5	2.8	19.0	1.2	12.7	2.1	1.9	0.5
15.5.	16.5	1.9	18.4	1.1	13.5	1.1	1.7	0.3
16.5.	12.7	1.7	16.7	1.9	13.2	1.7	1.6	0.3
18.5.	11.7	2.0	16.7	1.9	14.6	1.2	2.1	0.4
19.5.	12.2	2.5	17.9	2.1	13.6	1.2	2.0	0.4

Tar content of raw gas

Tar samples were taken from the product gas using the standard sampling protocol of VTT [2]. Table 5 presents a summary of the tar results with the two feedstocks used. The tar content of the gas varied according to the operation of the gasifier. This was indicated by the large standard deviation of the tar content. An example of this variation during one test day (13 May) is shown in Figure 3. During stable operation periods of the gasifier (stable char bed), marked by a high content of H_2 and CO, fairly low tar contents were measured (TE-3 and TE-4). The results obtained at this point can be considered typical of well operating downdraft gasifiers, in which the pyrolysis products have been effectively decomposed in the hot char bed. During unstable periods the contents were higher and close to the values obtained for fluidised-bed gasifiers. It can be concluded that the product gas of the Martezo gasifier contained an amount of tar similar to that measured for other downdraft gasifiers. The high variation in the content was also a feature typical of the downdraft gasifiers.

There was no marked difference in the tar contents of the two feedstocks used and almost equal average tar contents were obtained (Table 4). Consequently, according to the data obtained, the tested feedstocks did not have any marked effect on gas tar content.

Table 4. Average tar content and the standard deviation of the content (mg/m^{3}n) with the two feedstocks used.

Component	Fuel and concentration of tar component in gas mg/m^{3}n			
	DW1		DW2	
	mean	STDV	mean	STDV
Benzene	1 223	448	1 236	26
Pyridine	10	10	0	0
Toluene	277	123	257	14
M-Xylene	30	12	26	1
Ethynylbenzene	19	17	21	6
Styrene	86	44	76	8
O-Xylene	12	5	11	1
Phenol	121	92	62	22
4-Methylstyrene	27	17	20	4
Indene	88	68	76	19
Naphthalene	239	120	222	5
Quinazoline	0	0	0	0
Isoquinazoline	0	0	0	0
2-Methylnaphthalene	27	14	23	2
1-Methylnaphthalene	19	9	16	0
Biphenyl	9	8	9	0
2-Ethylnaphthalene	0	0	0	0
Acenaphthylene	83	51	83	12
Acenaphthene	4	4	0	0
Dibenzofurane	5	6	3	4
Fluorene	12	9	11	2
Phenantrene	30	16	30	2
Anthracene	6	6	7	1
4H-Cyclopenta(def)phenanthrene	7	7	10	1
Fluoranthene	13	9	14	1
Benz(e)acenaphthylene	16	11	20	2
Pyrene	21	18	14	1
TARS (mp.> 79 g/mol)	1 161	651	1 010	97
TARS + BENZENE	2 383	1 097	2 246	71

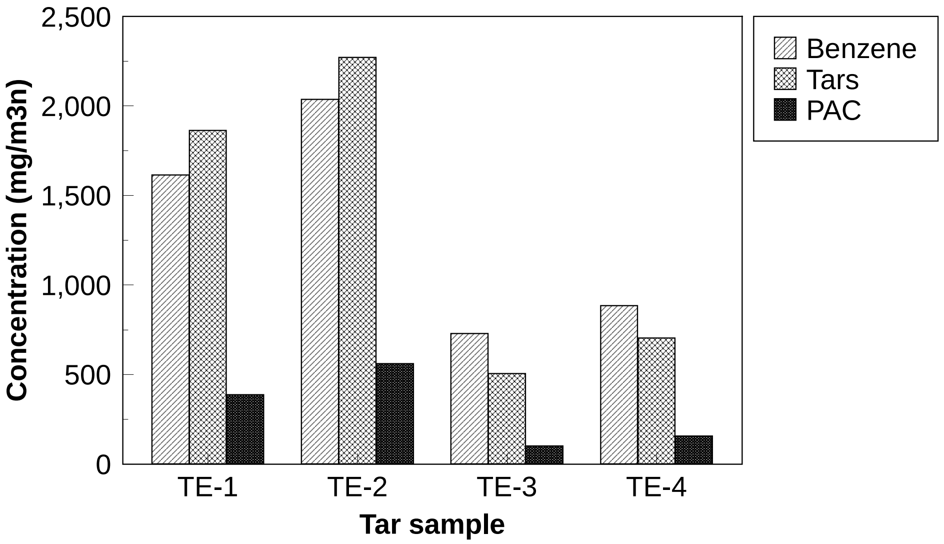


Figure 3. Tar contents measured for the product gas (before scrubber) during the test on 13 May 1998.

Gas scrubbing system

In the test on 19 May 1998, the tar samples taken before and after the scrubbing system were fairly representative of normal gasifier operation, and the results can be used for following tar removal efficiencies. The gas tar contents at the different sampling points are shown in Figure 4 and the removal efficiencies of the scrubbing system are presented in Table 5.

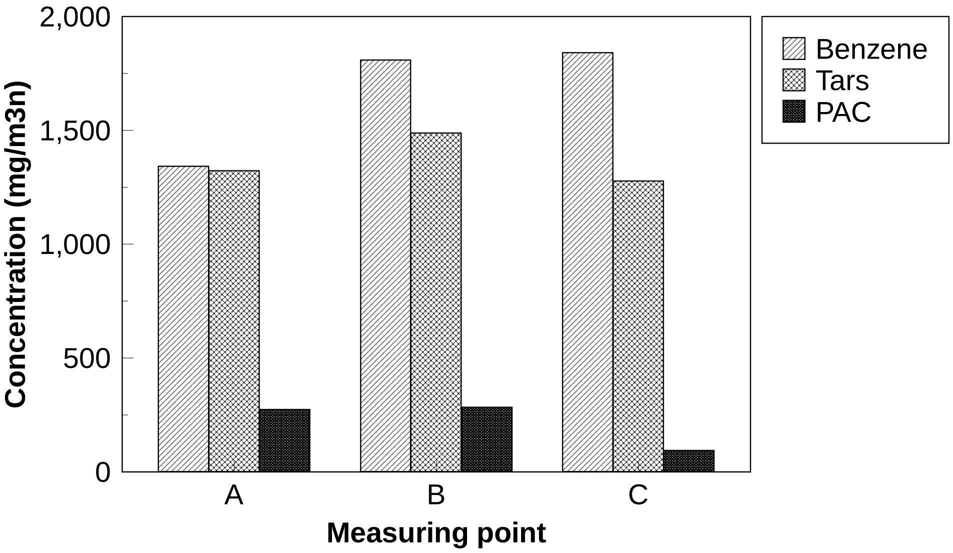


Figure 4. Tar content of gas after the gasifier (A), after the water scrubber (B) and after the sawdust filter (C).

Table 5. Removal efficiencies (%) of different tar compounds, compound groups and particulates in the gas scrubbing system.

Compound group	Water scrubbers	Saw dust filter	Total
Benzene	0	0	0
Phenol	76	100	100
Tar	0	14	3
PAC	0	67	65
Particulates	14	50	57

It can be concluded from the results that the water scrubber removed the water-soluble compounds like phenol efficiently, but was inefficient in removing tars and the most harmful tar fraction, the polyaromatic compounds (PAC). These results are consistent with earlier studies of the same subject [5]. Moreover, it was showed previously that the scrubbing efficiency can be enhanced by cooling the scrubbing water, but water at about 30 °C, as in this particular case, removes poorly non-water soluble compounds. At this temperature, the vapour pressures of lighter PAC compounds are still high enough to allow considerable gas-phase concentrations.

The sawdust filter also removed the water-soluble compounds, and also the heaviest tar compounds fairly efficiently. However, all tars were not removed as well and their content was still relatively high after the filter, in the range of 1 g/m^{3}n (PAC about 0.1 g/m^{3}n).

In order to characterise the environmental impact of the waste water produced by the scrubber, water samples were taken during the test run on 19 May 1998 from the scrubber effluent stream. The average amount of produced waste water was also determined in the test run on 19 May 1998, and it was 18 l/h (in this test the engine output was 40 kVA). The total organic carbon (TOC) content of the samples was on average 800 ppm. This result is comparable to previous studies of VTT Energy concerning water scrubbing of downdraft gasifier gas [5, 6]. In these experiments, similar TOC values were obtained for the water scrubber that worked on the almost total circulation of scrubbing water. Based on the previous results [6] the total oxygen demand (TOD) of this type of water is about 3 x TOC, which hence gives about 2 400 ppm for TOD. Typically, this type of water is rich in phenolics and other water-soluble compounds and also in easily condensable heavy polyaromatics. This in turn means that the waste water contained high amounts of environmentally hazardous compounds. Consequently, it can be concluded that the water effluent of the Martezo gasification process has to be purified before it can be disposed to a municipal wastewater system or to the environment.

2.2.4 Results for other biomass fuels

Due to the unsteady operation of the gasifier also with the relatively high-grade wood blocks tested in the first test campaign, the programme of the second test campaign was somewhat changed and reduced from the original plan. Tests were carried out with wood briquettes and with robinia chips mixed with the design wood fuel. Briquetting or pelletisation makes it possible to produce a homogenous feedstock, which also has a much higher bulk density than that of ordinary wood chips. Moreover, different additives can also be mixed in the fuel during the densification process. This may enable the use of such ash-containing fuels that otherwise would cause sintering problems in the reactor.

The tests runs of the second test campaign were started by carrying out firstly an additional test with design wood (mixture of DW1 and DW2) followed by tests with saw dust briquettes and mixtures of local biomass residues (Table 6). During this test campaign, the staff of Dr. Luca Poletti of Sereco-Biotest, Perugia, carried out the gas analysis and the other measurements.

The test run with wood briquettes were carried out without operation problems and the gas composition and its variation were rather similar to those in previous tests with the design wood. However, with sawdust briquettes the grate had to be agitated more often than with the design wood blocks. This was due to the fact that the briquettes were partly broken in the gasifier, which created a higher pressure drop.

Table 6. The downdraft gasification test runs carried out with saw dust briquettes and robinia / design wood mixture in 1999.

Day	Feedstock/ output	Aim of the test	Experiences
10.8.1999	DW1 -> SD briquettes 20 - 25 kVA	Change from design wood to wood briquettes	Start up of engine at 10:00 and shut down at 20.00. Successful test, stable operation of the plant, pressure drop of the gasifier and the sawdust filter remained stable. Fuel was changing at the end of the day, which was seen as increased need for rotating the grate.
11.8.1999	SD briquettes 25 - 30 kVA	Whole day with briquettes	Start up of engine at 09.55 and shut down at 17.30. Successful test, stable operation of the plant, pressure drop of the gasifier and the sawdust filter remained stable.
27.9.1999	DW1 & robinia chips 50% / 50%	Whole day with the fuel mixture	Large variation in gas composition, very unstable operation, break through of oxygen (indicating bad channelling in the bed)

In the final test run, a 50%/50 % mixture of design wood blocks and robinia wood chips was used as the feedstock. This test run clearly showed that this type of gasifier cannot be operated with inhomogeneous wood mixtures that also contain small particles. The operation was very unstable, which was seen as a large variation in the pressure drops of the reactor as well as in gas composition. Occasionally, there were high concentrations of oxygen in gas indicating severe channelling in the bed. The engine also stopped a couple of times during the day and it was very difficult to keep it operating with this kind of poor quality gas.

2.2.5 Examination of the test facility after the test campaigns

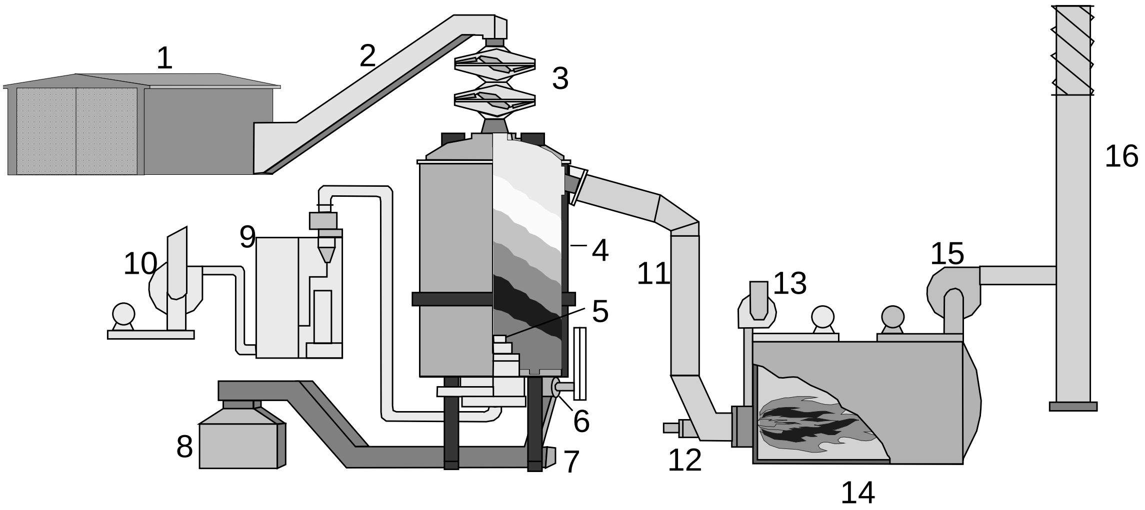
When the 1999 test campaign was finished, the engine was opened for final inspection. No serious deposits were found in the engine. This indicates that the achieved level of gas purity was enough for this naturally aspirating engine. Evidently, the saw dust and cloth filter removed sufficiently the residual heavy tars and soot from the gas and protected the engine.

2.3 Performance of a standard updraft gasifier with different biomass fuels

2.3.1 Operating experiences with different fuels at Bioneer gasification plants

A fixed-bed updraft gasifier was developed and commercialised in the early 1980s in co-operation with VTT and Finnish SME's [6]. Eight gasifiers (product name Bioneer) were constructed by Perusyhtymä Oy in the mid 1980s with outputs of the order of 5 MW_{th}. In addition, Foster Wheeler Energia Oy built one new gasifier in 1996. These gasifiers were close-coupled to small district heating boilers and drying kilns and have all operated very successfully. All plants are still in operation. A schematic diagram of a Bioneer district heating plant is shown in Figure 5.

The use of fuels, the plant efficiencies and the emissions were updated on the basis of Finnish gasification plants, as these give a sufficient basis for a reliable assessment of the present status. These data are presented in Table 7, which also includes a short summary of the Swedish gasifier plants.



1. Fuel storage
2. Fuel conveyor
3. Fuel feeder
4. Gas generator
5. Grate
6. Ash removers
7. Ash coveyour
8. Ash balette
9. Humidifier
10. Gasification air fan
11. Gas pipe
12. Gas burner
13. Combustion air fan
14. Gas boiler
15. Flue gas fan
16. Stack

Figure 5. Bioneer updraft gasifier in district heating application [6].

The original fuel requirements given by the manufacturer (Perusyhtymä Oy) were as follows:

- Moisture content less than 50% of the weight of moist fuel
- Ash amount less than 10 wt% of dry matter
- Minimum softening point of ash > 1 190 ^{o}C (DIN 51730)
- Heat value 0.65 - 1.7 MWh/ m^3

In addition, the manufacturer has given the minimum and maximum values for the piece size of the fuel. These values are dependent on the dimensions of the conveyor system and on the requirements of the gasification process. The main fuels of the gasification plants in operation in Finland have been sod peat and wood chips. The fuel characteristics given in Table 5 are typical and have met the requirements of good operational economy in practice. The most significant deviation from the specification given by the manufacturer is the maximum moisture content, which shall hardly ever exceed 45% in practice, and shall not exceed 40% if the peak efficiency of the gasifier is required over a longer time. The main reason for this limitation is that the combustion of the low-temperature product gas containing a lot of tar aerosols and water vapour becomes unstable as soon as the moisture content exceeds 45%. No lower limit has been found for the moisture content in practice, not even due to safety issues.

Table 7. Commercial updraft fixed-bed gasification plants in Finland - technical and economic data from 1997.

Owner Name	Jalasjärven Lämpö Oy	Kauhajoen Lämpöhuolto Oy	Kiteen Lämpö Oy	Oulun Seudun Lämpö Oy	Parkanon Lämpö Oy	Ilomantsin Lämpö Oy	Remarks
Commissioning	1987	1985	1986	1985	1986	1996	
Commissioner	Perusyhtymä Oy	Perusyhtymä Oy	Perusyhtymä Oy	Perusyhtymä Oy	Perusyhtymä Oy	F-W Oy	
Special features	Cond. heat recovery						
Technical data							
Capacity with solid fuels MW	**5**	**5**	**6**	**5**	**4**	**6**	Nominal efficiency
Other capacity MW	4 oil	9 oil	8 oil	4 oil	5 oil	5, another solid fuel combustor (grate)	Equiv. To peak load, no reserve capacity included
Annual production MWh	26600	41800	37000	23000	26000	40000*	* Gasifier boiler: 16300 MWh
Sales, MWh	23000	37500	34100	20500	22000	33000	
Emissions							
Dust	3 mg/MJ	4 mg/MJ	40 mg/MJ	30 mg/MJ	33 mg/MJ	15 - 183 mg/MJ*	* with wood chips: 10-18, with peat 25-183
Fuel/amount MWh/year							
Sod peat	23000	35200	4600	22900	19000	14600*	* used in gasifier
Wood chips	1000	100	25100			14200*	* 3000MWh in gasifier, the rest in grate boiler
Other biomass	200		7100		1000	13900*	* used mainly in grate boiler
Oil	4300	13000	6400	4600	10000	3500	
Total	28500	48300	43200	27500	30000	46200	
Electricity consumpt./ MWh	465	605	850	385	375	1222	Total electricity, incl. pumping of district heat
kWh/ MWh(generation)	17.48	14.47	22.97	16.74	14.42	30.55	
Characteristics: moisture/ density %/kg/m^3							
Sod peat	20-45/280-450	20-40/280-420	28-38/320-400	30-45/280-400	28-43/300-430	35-38/	Limits of variation
Wood chips	30-45/220-270		30-42/230-280			25-40/240-300	
Other biomass	10-20/220-260		8-12/280-320		12-18/180-230		
Costs FIM/MWh							
Investments (MFIM)	10 MFIM	9,2 MFIM	11,8 MFIM	7,8 MFIM	5,5 MFIM	20 MFIM*	* Includes 9 solid fuel boilers (gasifier and grate)
Fuel costs	50.9	63.1	59.0	56.9	63.4	65.0	Price, VAT 0%
Other production costs	16.5	14.9	20.4	15.0	27.1		
Total variable costs, wages excl.	67.4	77.9	79.4	71.9	90.5		
Total efficiency	0.81	0.78	0.79	0.75	0.73	0.71	Incl. production, distribution and measuring losses
Production efficiency	0.93	0.87	0.86	0.84	0.87	0.87	

Plants in Sweden	Byggelit, chipboard factory, Lit	Byggelit, chipboard factory, Lit	Vilhelmina Värmeverk AB, Vilhelmina
Year of commissioning	1986	1986	1986
Commissioner	Perusyhtymä Oy	Perusyhtymä Oy	Perusyhtymä Oy
Use	hot-water boiler	energy source of chip drier	district heat boiler
Capacity	4 MW	5 MW	5 MW
Fuel	waste from chipboard factory, wood chips	waste from chipboard factory, wood chips	sod peat
Present status	in continuous commercial use	in continuous commercial use	in commercial use as the peak and reserve boiler of the district heat network

The ash content of Finnish peat is usually clearly below the operability limit, and there is no clear indication of crust caused by passing below the fluid temperature of ash that had prevented the operation. However, care should be taken of the operational safety and sufficiency of humidifying of the gasification air, as well as the condition of the grate. The main rule is that the cases of crust are the rarer the longer the experience of the operating personnel.

The dimensions and percentage distribution given for the piece size of the fuel describe rather poorly the suitability of different fuels for fixed-bed gasification, with the exception of the maximum piece size. Assessment of the criterion of gas permeability is fairly easy in practice. On the other hand, the flowability of the fuel is an important criterion when assessing the behaviour of the fuel batch in the process. The good flowability is necessary primarily as there are points in the conveyor system and feeders, where the gravity and flowability of the fuel is utilised. In addition, a sufficiently low flow angle of the fuel is required as it enables the formation of a satisfactorily operating fuel bed inside the generator. In addition to the piece shape and size distribution, flow properties are indicated by weight per cubic meter of the fuel or fuel mixture. A rule of thumb is that this weight should be >200 kg/m^3, when there are good possibilities of flowing and the radioactive detector used for surface measuring in the generator identifies the surface of the fuel bed.

The practice has also shown one characteristic that affects the availability of the fuel, i.e., how much tars are formed in gasification. The tars foul the gas pipe leading from the gasifier into the boiler and shorten the period after which the gas pipe must be cleaned by burning the tars.

On the whole, fixed-bed updraft gasification has proved to be a good and economically feasible combustion method in small district heating systems. Fuel requirements are not unreasonably stringent considering the requirements of the process. However, several potential fuels, such as crushed bark, saw dust and crushed demolition wood cannot without problems be used at these plants (due to fuel flowing problems). In addition, the use of updraft gasifier gas without further gas treatment is limited to applications, where the gas can be burned close to the gasifier.

2.3.2 Gasification tests with Italian biomass feedstock

Finesport supplied 23 tons of coppice wood chips from Umbria region to the Bioneer district heating plant located in Jalasjärvi Finland. These tests were organised by Jalasjärven Lämpö Oy. The performance of the plant with this new fuel was determined during 33 hours of continuous operation. During this time the plant was operated at 2.2 - 3.2 MW load depending on the need for district heat in Jalasjärvi.

During these tests, the gasifier performance was excellent and no problems were met. The main conclusion from the test run was that this Italian coppice wood was very suitable to the standard updraft gasifier, and this experience created the required technical basis for designing a commercial demonstration plant to Umbria (for close-coupled combustion applications).

2.4 Development of a new gasifier based on forced fuel flow

2.4.1 Novel gasification pilot plant

The aim of this task of VTT and Condens in the project was to develop and test a new type of fixed-bed gasifier, which is based on forced fuel flow and consequently allows the use of low-bulk-density (of the order of 150 - 200 kg/m^3) fibrous biomass residues. The aim was to construct a pilot plant, which is of the equal quality as the commercial gasifiers and could be directly scaled up to the first demonstration plant. The nominal design capacity of the pilot plant was 300 kW_{th}. The design work was carried out in close co-operation between Condens and VTT, who also had jointly invented this gasification concept before starting this project.

The pilot plant (Figure 6) is located in the gasification test hall of VTT Energy in Espoo Finland. It can be operated continuously. The pre-weighed batches of fuels are fed into the first reception pocket of the fuel feeding equipment by a front-end loader. From the reception pocket the fuel is transported through two lock hopper feeders into an intermediate fuel silo. This arrangement made it possible to avoid any gas leakage into the test hall. The silo to the fuel feeding device introduced the feedstock into the gasifier reactor. The product gas leaving the gasifier was led into the secondary cracking unit, which can be operated either as a thermal cracker or as a nickel-monolith unit. Additional air was introduced before the cracker in order to achieve the target operation temperatures required for tar decomposition.

2.4.2 Feedstocks and test runs

In total four gasification test runs were carried out in the period of February - June 1999. The gasified fuels and realised set points of these test runs are presented in Table 8 and the feedstock properties in Table 9. All feedstocks were thermally dried, as the aim of the project was mainly to produce a gas suitable for engine use. However, later tests have shown that this gasifier can also be operated with high-moisture fuels, but then the low heating value gas produced must be combusted in a boiler or other close-coupled applications.

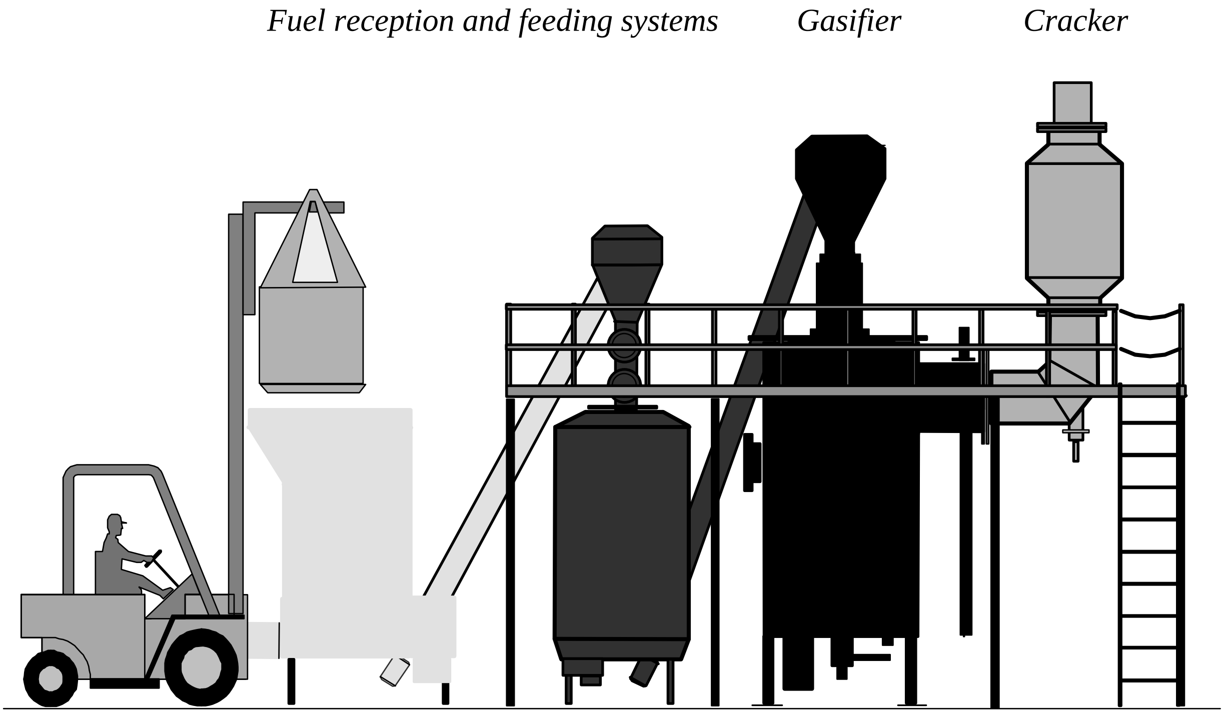


Figure 6. Schematic diagram of the Novel fixed-bed gasifier pilot plant.

In these test runs no major technical problems were met and the gasifier performance was determined for all planned test fuels. The first test run NOV 99/5 was intended for testing the gasifier performance at different loads and different operating conditions. Forest wood residues were used as the fuel. The set points were scheduled to daytime, while the gasifier was left hot but without fuel feeding over nights. In the second test run NOV 99/11, the gasification behaviour of three other feedstocks was determined. In these two first test runs, the secondary catalyst chamber was operated without the monolith elements.

The main aim of test runs NOV 99/17 and NOV 99/23 was to test the performance of the secondary nickel-monolith catalyst unit under different operating conditions. The effects of gas residence time, catalyst and gasification operating temperatures were determined. In addition, new data was created for the gasifier using crushed bark as the feedstock.

Table 8. Test runs and set points realised at the Novel gasifier pilot plant.

Set point - date	Length h	Fuel	% of nominal design capacity	T gasification °C	T at cracker °C[2)]
NOV 99/5A - 2.2.99	5	FWW1	67	745	810
NOV 99/5B - 3.2.99	8	FWW1	100	660	710
NOV 99/5C- 4.2.99	3	FWW1	40	740	750
NOV 99/5D - 4.2.99	4	FWW1	67	690	850
total test run time[1)]	60				
total time with fuel feeding	35				
NOV 99/11A - 17.3.99	9	FWW2	67	770	825
NOV 99/11B - 17-18.3	10	FWW2	100	750	810
NOV 99/11C - 18.3.99	5	SRW	80	740	850
NOV 99/11D - 19.3.99	5	PSD	80	760	865
total test run time	69				
total time with fuel feeding	63				
NOV 99/17A - 28.4.99	9	FWW2	67	820	880
NOV 99/17B - 28.4.99	4	FWW2	67	765	950
NOV 99/17C - 29.4.99	6	FWW2	45	720	930
NOV 99/17D - 29.4.99	3	FWW2	33	675	925
total test run time	43				
total time with fuel feeding	43				
NOV 99/23A - 8.6.99	3	FWW2	67	730	950
NOV 99/23B - 9.6.99	7	BARK	67	725	920
NOV 99/23C - 9.6.99	8	BARK	100	720	925
total test run time	37				
total time with fuel feeding	37				

[1)] Total test run time from starting the fuel feeding to the beginning of the final shutdown procedure

[2)] In tests 5/99 and 11/99 the cracker was empty and the temperature was measured at the reactor outlet, in tests 17/99 and 23/99 the cracker temperature was the average temperature of the monolith catalyst unit.

Table 9. Composition of the feedstocks tested in test runs of the Novel pilot plant.

	FWW1	FWW2	SRW	PSD	BARK
Moisture content, wt%	11	10	10	10	7.2
Bulk density, kg/m^3	263	245	178	190	230
HHV (dry basis), MJ/kg	20.9	20.9	19.8	20.3	20.4
LHV (dry basis), MJ/kg	19.6	19.6	18.6	19.0	19.1
Volatile matter, wt% d.b.	76.6	76.8	77.7	82.9	75.6
Ultimate analysis, wt% d.b.					
C	51.0	51.8	50.2	50.9	51.3
H	6.1	5.8	5.6	6.2	5.9
N	0.7	0.5	0.4	0.1	0.3
S	0.05	0.04	0.04	0.01	0.02
O (as difference)	40.05	39.76	41.36	45.59	42.48
Ash	2.1	2.1	2.4	0.2	1.6
Sieve analysis, wt%					
> 31.5 mm	-	2.4	0	-	0
16.0 - 31.5 mm	-	12.0	2.5	-	11.2
8.0 - 16.0 mm	0.1	23.4	19.9	-	41.7
3.15 - 8.0 mm	38.7	25.9	39.1	-	28.0
2.0 - 3.15 mm	17.5	12.6	19.0	19.5	5.5
1.0 - 2.0 mm	24.4	16.3	10.5	34.4	5.5
< 1.0 mm	19.3	7.4	9.0	46.1	8.1

FWW1 = Forest wood residue chips crushed and sieved to below 6 mm size
FWW2 = Forest wood residue chips as received
SRW = Short rotation willow chips, PSD = Pine saw dust

2.4.3 Results

The running of the gasifier was smooth in all the test runs performed and it was easy to reach the set point conditions. The gas composition varied slightly due to variations in fuel feeding. In tests carried out in a later project this problem was eliminated by small changes in the forced fuel feeding system. However, even before this modification the observed variation was fairly small compared to the downdraft gasifier.

The mean contents of the main gas components, H_2, CO, CO_2 and CH_4 during all the test runs performed are presented in Table 10. Compared to the results obtained with the Martezo downdraft gasifier and the Bioneer updraft gasifier it can be stated that the product gas composition of the Novel gasifier is closer to that of the updraft gasifier, which is natural as the lower part of the Novel reactor is operated in counter-current principle.

The mean contents of benzene, tars and ammonia during all the test runs are presented in Table 10. The tar in this context means compounds from toluene to pyrene (bp. 120 -

400 °C). Table 11 presents an example of the typical contents of the tar compounds at the gasifier exit.

Table 10. Mean dry gas analysis after the gasifier during the performed test runs.

Set point - date	H_2 vol%	CO vol%	CO_2 vol%	CH_4 vol%	Benzene mg/m^3_n	Tar mg/m^3_n	Ammonia mg/m^3_n
NOV 99/5A	9.2	24.0	9.3	3.7	4 351	3 869	-
NOV 99/5B	9.6	27.0	7.6	3.3	2 610	2 480	-
NOV 99/5C	7.4	18.1	11.8	2.9	3 657	1 519	-
NOV 99/5D	9.9	25.6	8.4	3.7	1 532	1 720	-
NOV 99/11A	8.4	22.6	9.1	3.0	4 608	3 629	-
NOV 99/11B	9.0	25.7	8.2	3.4	3 455	2 557	-
NOV 99/11C	9.2	24.6	10.1	3.7	3 992	2 828	-
NOV 99/11D	9.5	24.1	10.3	3.7	4 143	2 932	-
NOV 99/17A	8.7	19.0	10.6	2.5	2 051	1 640	847
NOV 99/17B	10.4	23.5	9.0	3.6	5 118	4 150	779
NOV 99/17C	9.7	21.3	9.7	3.2	3 662	3 036	615
NOV 99/17D	9.3	21.9	9.9	3.4	3 882	6 253	495
NOV 99/23A	10.3	21.7	10.6	3.3	4 817	3 498	-
NOV 99/23B	15.8	17.1	12.2	1.0	4 698	4 654	-
NOV 99/23C	10.6	27.1	8.0	3.6	3 773	3 566	-

The tar content of the gas and the tar composition measured from the Novel gasifier were fairly similar to values obtained for a fluidised-bed gasifier, in which calcium-based bed additive is used. Consequently, the values were more than an order of magnitude lower than those typically measured for an updraft gasifier. The tar contained naphthalene, toluene and polyaromatics as the main components, indicating that tar cracking took place in the hot zones of the gasifier. According to VTT experiences from fluidised-bed gasification processes, this type of gas can be cooled down to 200 - 400 ^oC and filtered within this temperature range without tar condensing problems. However, considering the usability of gas in an engine, further tar removal/decomposition is definitely required.

The ammonia content of the gas was monitored during test run NOV 99/17 when wood residues were used as feedstocks. Again, the content was fairly close to that observed in fluidised-bed gasifiers for the same types of fuel. The hydrogen cyanide content in the same run, period 99/17A, ranged 460 - 510 mg/m^3n.

The dust content of the product gas was determined only after the thermal/catalytic tar cracking reactor, as it was not possible to take representative isokinetic samples from raw gas before the cracking unit. The dust content presented in Table 12 ranged 90 - 580 mg/m^3n, which is significantly lower than the contents determined for fluidised-bed gasifiers by VTT.

Table 11. Mean contents of benzene and the tar components at gasifier exit (mg/m$^3{}_n$).

Compound Set point	99/23 A	99/23 B	99/23 C
Benzene	4 817	4 698	3 773
Pyridine	110	71	52
Toluene	388	634	497
m-Xylene	21	49	35
Ethynylbenzene	10	23	21
Styrene	159	249	186
o-Xylene	0	17	12
Phenol	677	905	514
4-Methylstyrene	105	141	99
Indene	111	200	175
Naphthalene	1 079	1 208	1 007
Quinoline	0	0	0
Isoquinoline	0	0	0
2-Methylnaphthalene	45	87	66
1-Methylnaphthalene	31	59	44
Biphenyl	57	70	53
2-Ethylnaphthalene	0	0	0
Acenaphthylene	226	294	271
Acenaphthene	11	14	9
Dibenzofurane	109	110	80
Fluorene	21	35	30
Phenantrene	168	243	205
Anthracene	29	47	40
4H-Cyclopenta[def]phenanthrene	5	19	17
Fluoranthene	62	79	74
Benz[e]acenaphthylene	17	20	19
Pyrene	56	77	60
TARS (mp.> 79 g/mol)	3 498	4 654	3 566
TARS + BENZENE	8 314	9 353	7 339

2.5 Development of catalytic gas cleaning for engine use

The original objective of this task of the project was to develop and test, on the pilot scale, a simple and reliable secondary catalytic reactor required for complete decomposition of tars. This development work was a direct continuation for the extensive previous catalytic gas cleaning R&D carried out at VTT [7].

The experimental work of this task was started by connecting the secondary tar cracking reactor to the Novel gasifier. The test work was started by using an empty reactor as the secondary thermal cracker and the tar concentration was determined after this secondary thermal cracking reactor in test runs NOV 99/5 and NOV 99/11. Then two different arrangements with the nickel monolith catalysts were tested in test runs NOV 99/17 and NOV 99/23. The temperature of the reactor was controlled by the amount of cracking air (between 750 - 980 °C).

The average operating temperature of the catalyst unit as well as a summary of the gasification conditions are presented in Table 8. The mean contents of the main gas components, H_2, CO, CO_2 and CH_4 and contaminants after the cracking unit during all the performed test runs are presented in Table 12.

Compared to the gas composition before catalyst (Table 10) it can be concluded that H_2 and CO_2 contents of the gas increased and CO decreased during catalytic treatment. Quite obviously this change in composition was caused by the water-gas shift reaction. Tar conversion was high, 91 - 99% during runs 17 and 23, and the obtained tar content, less than 100 ppm in the reformed gas, can be considered sufficiently low to allow the engine use without clogging problems. The ammonia content decreased, but was still higher than the allowable 50 ppmv for engine use. Thus, further scrubbing of gas to remove the residual ammonia seems to be required. However, the gas residence time was very short compared to other industrial applications (e.g. steam reforming) employing these types of catalyst, and thus, lower ammonia contents can most likely be obtained by increasing the catalyst volume.

After each test run, the servicing flanges of the catalyst reactor were opened and the system was inspected for possible deposits. However, no deposit was found.

Table 12. Mean gas composition after the cracking unit during the performed test runs. (na = not analysed).

Set point	H_2	CO	CO_2	CH_4	Dust mg/m^3_n	Benzene mg/m^3_n	Tar mg/m^3_n	Ammonia mg/m^3_n
NOV 99/11A	na	na	na	na	130	3 780	1 772	na
NOV 99/11B	na	na	na	na	90	na	na	na
NOV 99/11C	na	na	na	na	250	1 377	341	na
NOV 99/11D	na	na	na	na	580	1 966	564	na
NOV 99/17A	12.7	14.4	13.4	1.9	90	1 261	930	na
NOV 99/17B	14.8	16.5	12.2	1.1	na	63	14	101
NOV 99/17C	13.2	14.5	12.7	1.0	na	68	93	217
NOV 99/17D	13.2	14.3	12.7	1.0	na	101	92	37
NOV 99/23A	14.1	14.6	13.2	0.7	na	59	143	na
NOV 99/23B	15.8	17.1	12.2	1.0	na	79	62	na
NOV 99/23C	16.9	19.7	11.1	1.1	na	119	129	na

2.6 Technical feasibility and markets of small-scale gasifiers

The process concepts studied in this project are summarised in Table 13, and in the following the markets and competitiveness of these concepts are discussed and compared with competing technologies available for small-scale (1 - 10 MW_{th}) heating and combined heat and power production.

Table 13. The different process concepts studied in this project.

Gasifier	Status	Application	Size range	Fuel quality requirements	R&D tasks in this project
Standard downdraft	Commercial	Power production by engine	<0.5 MW$_e$	Piece-shaped dry wood with a low ash content	Reliable tar data with a range of fuels, and trials to broaden the fuel basis by mixture fuels
Novel countercurrent	A prototype of different design was tested before this project	Heat production: district heating and dryers & kilns	1 - 10 MW$_{th}$	Biomass residues with minimum pretreatment	The gasifier was developed and tested on pilot scale. Secondary catalytic reactor was developed and tested on pilot scale
		Power and heat by engine	500 - 3 000 kW$_e$	Storage dryer to lower moisture to <25%	Clean gas suitable to engine use can be produced
Standard updraft (Bioneer type)	Commercial	Heat production	1 - 8 MW$_{th}$	Moisture <45% Fines <20% Ash melting >1 000 °C	Used as reference in studies. Collection of operating experience from nine commercial Bioneer plants. Tests with Italian biomass
	Plant designed but not built	CHP based on steam cycle	1 - 5 MW$_{heat}$ 1 - 2 MW$_e$		
	Concept	CHP production based on engine	2 - 4 MW$_{heat}$ 1 - 4 MW$_e$	Moisture <25%	Catalytic cleaning developed for the Novel gasifier can also be used in standard updraft gasifiers

2.6.1 Heat alone production

Both the standard updraft gasifier (such as Bioneer) and the new Novel fixed-bed gasifier are technically suitable for producing district or process heat or hot gas for drying kilns. The Novel fixed-bed gasifier has larger markets, as it is suitable for a wider range of biomass fuels, while the commercially available fixed-bed gasifiers are limited mainly to sized feedstocks. The downdraft gasifier should not be considered for heating applications due to the following three facts: a) very stringent requirements for fuel quality, b) lower carbon conversion efficiency and c) more unstable operation (bed channelling etc.).

However, there are many competing direct combustion technologies for small-scale district/ process heat production. In the mid-1980s the Bioneer updraft gasification heating station was both technically and economically very competitive with direct combustors in Finnish and Scandinavian markets (grate combustors and small fluidised-beds). Since then, different new types of grate combustor have been developed, which can compete with the Bioneer plants. The main technical limitations and problems of Bioneer plants were: a) the gasifier is not suitable for low-bulk density wood residues (such as crushed bark, saw dust and forest residues), b) if the moisture content of the fuel was above 45%, gas combustion became unstable, c) the gas pipe was clogged by tars and had to be cleaned by burning once in 1 - 4 weeks and d) the fuel feeding systems leaked slightly. In other respects the commercial Bioneer updraft gasifiers have been working very well since the mid-1980s. Based on the pilot gasification tests, it seems that all the limitations of the Bioneer gasifier listed above have been more or less eliminated in the design of the Novel gasifier. As the estimated investment cost of the Novel gasifier is very close to that of the Bioneer plant, the market perspectives for this new gasification-based heating system are fairly good. The estimated investment cost of a turn-key delivery of a complete Novel gasification heating plant for producing district heat from wood residues is 0.35 - 0.42 MEUR/MW_{th}. This is very close to the realised investment costs of recent Finnish district heating plants based on competing direct combustion technologies [8].

The main technical advantages of the Novel gasifier in heating applications are:

- Fuel flexibility: particle size from saw dust to crushed bark and coarse wood chips, probably the moisture content can also be higher than in Bioneer gasifiers due to the fact that the combustion of hot low-tar gas is more stable than that of cold gas that contains an abundance of tar aerosols (*this was verified in later tests, in which crushed bark of 55% moisture was successfully tested*).
- The fuel feeding method is fully automatic without requirements for level control or any other sensors or measurements.
- Existing oil or natural gas fired boilers can be used, which is a general advantage of gasification-based systems over other biomass combustion methods.
- If the fuel contains chlorine, poisonous organic compounds can be formed in direct combustors, while these compounds are efficiently decomposed in well-controlled high-temperature combustion of product gas.
- The gas can also be used for producing hot gases for drying kilns or other process ovens.
- As the tar content of the gas is fairly low, the gas can be distributed without severe tar condensation problems. In addition, the gas can be further cleaned, e.g., by cyclones or filters without such obvious tar problems as in ordinary updraft gasifiers.

2.6.2 Electricity production

In the size class of less than 3 MW_e studied, the main alternatives for electricity production are:

- Gasifier or direct combustor combined with a small steam cycle: this alternative has a rather low power-to-heat ratio (due to inefficient small steam cycle) and the specific investments are high. On the other hand, this process concept is the only alternative that can be considered to be fully commercially available.
- Direct wood-fired gas turbines: these systems have been developed both in USA and in Europe, but so far none of the developments has been successful. The main reasons for this are: a) alkali metals released in combustion cause rapid corrosion in turbine blades, b) pretreatment of wood into dry powder is expensive, and feeding of pulverised wood into pressurised combustors is also problematic.
- Stirling engines seem to approach commercialisation and their best market may be in the smallest size range (<500 kW_e). The recent development in Denmark seems to be promising, but probably a few years are still required until the technical and economic performance of Stirling engines can be reliably estimated. Small-scale gasifiers may also have some advantages compared to direct combustion based systems in Stirling applications (more easy to avoid erosion and corrosion and to control combustion conditions).
- Production of pyrolysis oil on a larger scale and distribution of produced oil to small-scale engine power plants: the technical feasibility of pyrolysis oil combustion in diesel engines has so far not been demonstrated, but there are several R&D projects going on and it is possible that this technology will become commercially available within a few years.
- Fixed-bed gasifiers coupled to diesel or gas engines are the focus of many R&D projects in Europe at the moment. There are several industrial development projects, e.g., in Switzerland, Germany, Denmark, UK and in the Netherlands, with which the fixed-bed gasification technologies (Novel gasifier combined with catalytic cleaning) will compete in the future. Most of the competing technologies are based on slightly modified classical downdraft gasifiers, such as that tested in Task B of this project. In Denmark and UK, there are also teams utilising updraft fixed-bed gasifiers and having tried to develop catalytic gas cleaning systems. However, so far these developments have not led to commercial breakthrough.

There are two basic alternatives to utilise the Novel gasifier for combined heat and electricity production. The gasifier can be connected to a steam boiler with a small steam turbine or the product gas can after cleaning be used in an internal combustion engine. Both alternatives were included in the techno-economic studies described in the following. It should be borne in mind, that the steam cycle can also be realised using competing direct combustion technologies (e.g. grate combustion) and it seems that the investment for grate combustion- based steam cycle is roughly the same as for the system based on the Novel gasifier and a product gas-fired boiler.

Based on the results and experiences obtained in this project and in previous R&D projects of VTT and Condens Oy, the commercial-scale gasifier-engine process concept was designed and the plant performance, investment costs and the electricity production costs were estimated. These costs were then compared to those of conventional steam cycle. The gas composition of an industrial-scale novel gasifier-catalyst unit was estimated using the measuring data for the pilot plant and the gasifier and cracker calculation models of VTT. The resulting estimate was as follows:

- Clean gas temperature = 40 ^oC and pressure = 0.1 MPa (abs)
- Main components: $CO = 13.9\%$, $H_2 = 18.4\%$, $CO_2 = 13.8\%$, $CH_4 = 1.9$, $H_2O = 7.3$ and $N_2 = 44.7$.
- Impurities: benzene < 40 ppm-v, ammonia < 10 ppm-v, dust < 20 mg/m^3n, no condensing tars

The suitability of the assessed cleaned product gas to turbo-charged gas engines was evaluated by contacting potential engine suppliers. Two engine suppliers informed that this gas can be fired in their engines. The performance of the Jenbacher engines in two size classes was calculated in detail, and budgetary offers were received from Jenbacher both for electricity alone and combined electricity and heat production. The investment costs of fuel handling and drying, gasification and gas cleaning sections of the plant as well the costs of buildings, auxiliary equipment and control and instrumentation were estimated by Condens Oy.

The performance and investment costs of the three size classes studied are presented in Table 14. The performance and costs of the reference conventional steam-cycle-based power plant (= Rankine) were taken directly from a study made by Energia Ekono for the Finnish market situation [8].

The cost of electricity was then calculated as a function of the annual operation time. The prices of biomass fuel and produced heat were used as parameters. The lowest fuel price of 0 Eur/MWh corresponds to a situation where there is no other use for a biomass residue, the medium price of 5 Eur/MWh is a typical price for bark and wood residues in Finland and the highest prices of 10 Eur/MWh corresponds to specially produced high-quality energy wood chips. Two prices for the produced heat were also studied: zero price for a case that only electricity is produced and a medium price corresponding to the average price of small-scale district heating plants in Finland. Fully automatic operation was assumed both for the gasifier-engine plants as well as for the reference steam cycle power plant. The operating costs were calculated on the basis of one full-time worker. The capital costs were calculated employing 5% interest rate and 20 year service time.

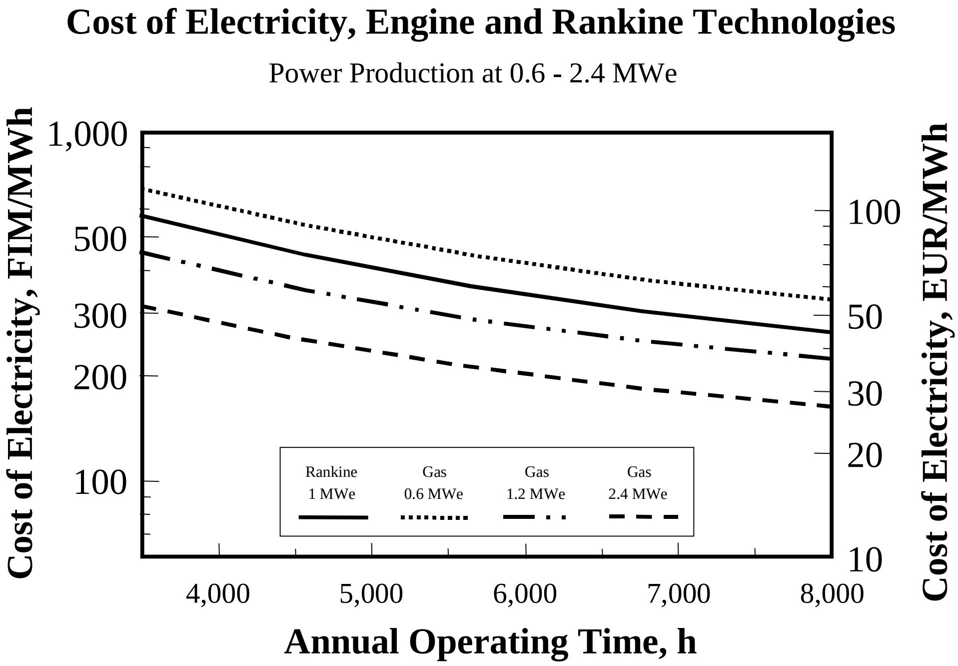
Table 14. The estimated performance and total investment of the Novel gasification-engine power plant in three size classes.

Size, kWe	Steam cycle	580	1 200	2400
Wood input, MJ/s (LHV based)[1]	5.6	1.7	3.3	6.7
Net power output, MWe	1.0	0.58	1.2	2.4
Heat production, kJ/s	4.0	0.87	1.73	3.55
Electricity efficiency, %	17.5	34.0	36.0	36.0
Heat efficiency, %	71.5	51.0	52.5	53.0
Total efficiency, %	89.0	85.0	88.5	89.0
Total investment, MEUR	2.84	1.8[2]	2.5[2]	3.6[2]
Relative investment, Eur/kWe	2 840	3 100	2 100	1 500
Relative investment, Eur/fuel-kW	510	1 060	750	540

[1] based on wood with 50% moisture, drying to 20% before gasification
[2] total investment of first commercial plants

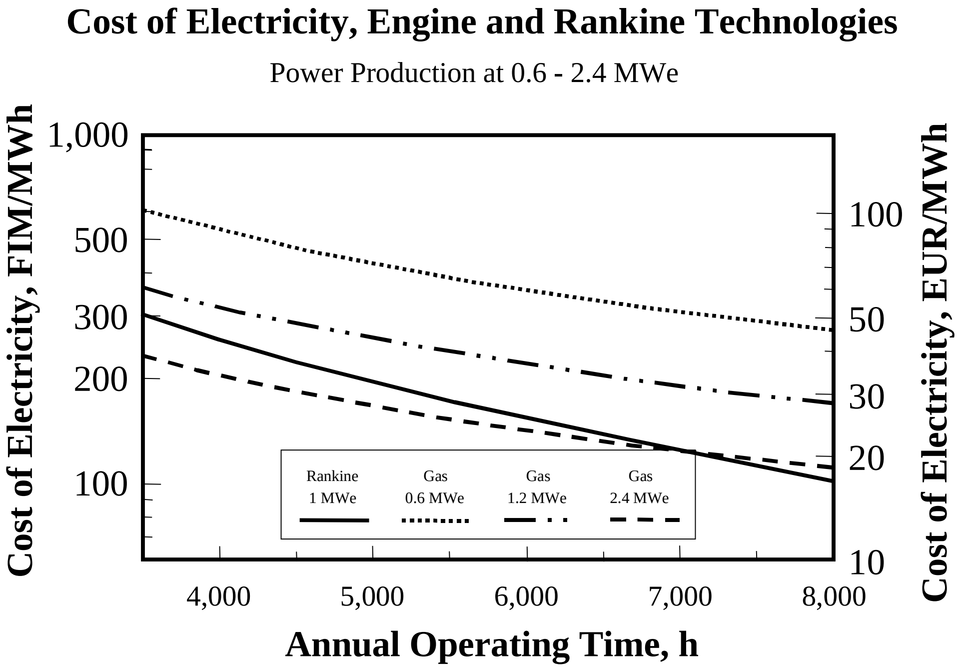
The results are shown in Figures 7 a-c. Figures 7 a-b show the effect of the income from the by-product district heat on the electricity price. These figures are based on using the medium fuel price of 5 Eur/MWh. The two larger-scale gasifier engine concepts seem to be competitive with the steam cycle when no district heat is produced. In the typical Finnish small-scale district heating case (Figure 7 b), only the largest gasifier-engine concept seems to be competitive with the steam cycle.

Figure 7 c illustrates the effect of higher fuel price on the competitiveness of the studied process concepts in a typical Finnish district heating application (with an average price for the produced heat). With higher fuel prices (10 EUR/MWh) the two larger-scale gasifier-engine process can compete with the steam cycle even in Finnish district heating case.



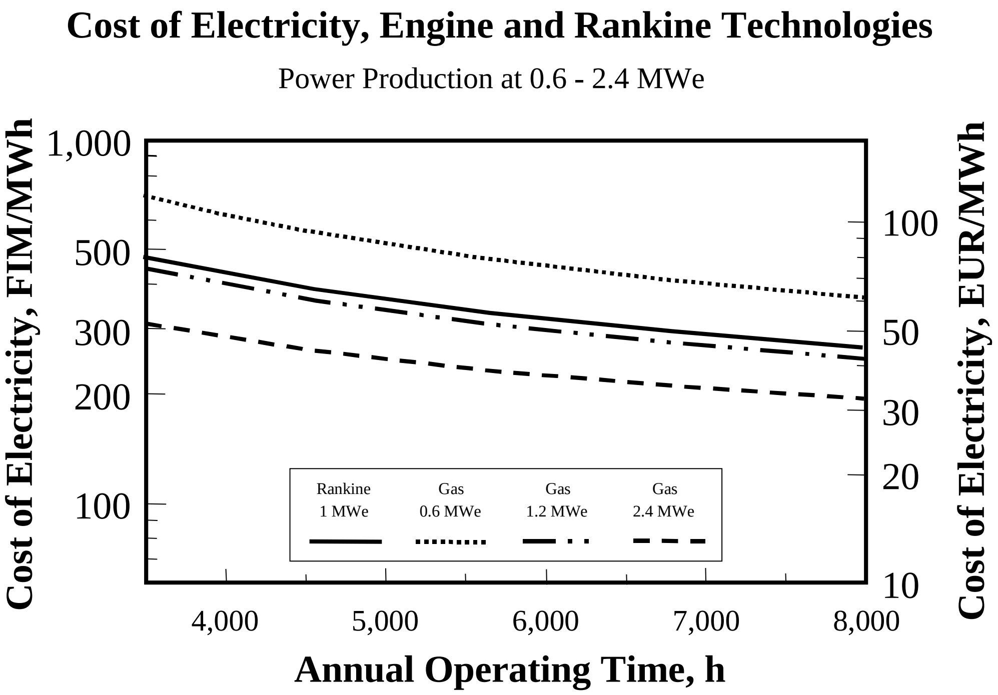
Wood Fuel 5 EUR/MWh (30 FIM/MWh)
No By-Product Heat
Capital Costs 5%, 20a

Figure 7a. The cost of electricity - medium fuel price (5 Eur/MWh), no by-product heat.



Wood Fuel 5 EUR/MWh (30 FIM/MWh)
Heat price with 150 FIM/MW, a (fixed) - 60 FIM/MWh (variable costs)
Capital Costs 5%, 20a

Figure 7b. The cost of electricity - medium fuel price (5 Eur/MWh), medium price for the by-product heat.



Wood Fuel 10 EUR/MWh (60 FIM/MWh)
Heat price with 150 FIM/MW, a (fixed) - 60 FIM/MWh (variable costs)
Capital Costs 5%, 20a

Figure 7 c. The cost of electricity - high fuel price (10 Eur/MWh), medium price for the by-product heat.

When these estimated electricity production costs are compared with the present electricity prices, none of the studied small-scale electricity production concepts (at biomass prices ≥ 5 Eur/MWh) is competitive with the prices paid for power producers when selling electricity to the grid. Thus, this kind of system can be competitive on the Finnish market only in two cases:

- If the produced electricity can be consumed without selling to the grid. Examples of this type of application are small sawmills, which have to pay a relatively high price (> 30 - 40 Eur/MWh) for their electricity.
- If the biomass-based power production is subsidised by an investment support, the subsidy for green electricity or taxation of fossil fuel is used for power production (at the moment only fuel for heating applications have to pay taxes).
- If feedstocks with a negative or zero price become available (e.g. due to changes in landfill regulations) and will be suitable for the new gasifier developed.

3. Conclusions

The following main conclusions are made on the basis of the results and experiences obtained in the different tasks of the project:

1. Most of the biomass residues available both in Italy and in Finland do not meet the requirements of commercial fixed-bed gasifiers. Usually the bulk density is low, the fuel is fibrous and also contains fines, which creates flowing problems in gasifiers relaying on natural gravity. In Finland, the most potential residues are crushed bark, forest residues and different residues from forest products industry and carpentry. None of these residues are well suitable to existing commercial fixed-bed gasifiers. In Umbria, the most potential fuels are residues from agriculture (e.g. from wine and olive trees) and small wood industries, local coppice wood and, in the longer term, short rotation forestry species. None of these fuels can be used without pelletisation in commercial downdraft gasifiers. Higher-grade chipped woody residues could be used in commercial updraft gasifiers.

2. Many agricultural residues contain high amounts of alkali metals, which may cause sintering and deposition problems in gasifiers. In the laboratory tests carried out in the projects, the ash sintering problems were avoided by using reactive additives such as kaolinite and paper ash.

3. The commercial downdraft gasifier tested in Italy operated best with sized wood blocks and with briquettes made of sawdust. Even with these ideal wood fuels, the operation was unstable and there were also some tars in the product gas. These tars blocked the sawdust and cloth filter a couple of times during the test runs. In addition, poisonous condensing and scrubbing water was produced, which may be very expensive to be disposed.

4. Several commercial updraft gasifiers (known as Bioneer) have been in reliable operation in Finland and Sweden for about 15 years. These gasifiers operate well with sod peat and wood chips, which have a moisture content of less than 45%. There have been only a few minor technical problems, and in general the availability of Bioneer plants has been very high. Test results obtained in the project at one of the commercial Bioneer plants with chipped Italian coppice wood were also very good. However, these gasifiers cannot be reliably operated with the existing Finnish wood residues (such as bark, saw dust and shavings) and other low-bulk density fibrous fuels, which do not flow down in the reactor without channelling problems.

5. The results obtained with the new gasifier design were even better than the goals set in the beginning of the project. All biomass residues tested were gasified smoothly and the gasifier performance was very good: carbon content of bottom ash <1%, dust elutriation less than 1 g/m^{3}n, tar content of gas <5 g/m^{3}n already at the gasifier exit.

The gasifier seems to be ready for larger-scale demonstration with various biomass residues (bark, shavings, saw dust, forest residues as well as chips from olive and wine trees). Further testing will be necessary to find the upper limit for the fuel moisture and to determine the ash behaviour of more problematic biomass fuels (such as straw). In addition, the suitability of different waste-derived feedstocks should be examined in the future R&D projects.

6. The tar content of the product gas was reduced to below 100 mg/m^3n by using the nickel-monolith catalyst unit. In addition, 70 - 90% of ammonia was also decomposed. Even lower tar and ammonia contents can be achieved by increasing the catalyst volume. No dust-related problems were met when the nickel-monolith catalyst unit was operated with the product gas derived from the Novel gasifier. However, before this technology can be commercialised, long-term tests (at least 1 000 - 2 000 hours) with real gases are needed.

7. The gas produced in the Novel gasifier and nickel-catalyst unit can, after simple water scrubbing, be used safely in modern turbo-charged internal combustion engines. A commercial-scale gasifier-catalyst engine plant was designed and its performance and costs were estimated. It seems to be possible to build a small-scale power plant, which has relatively high electrical efficiency (30 - 36%), can operate with a wide range of biomass fuels and does not produce any toxic waste water or other problematic emissions. The suitable size class of the plant seems to be in the range of 2 - 10 MW_{th}. However, this complete concept should be constructed and tested before any final conclusions from the technical and economic performance can be made.

8. The competitiveness of small-scale biomass-based electricity is at present very difficult to achieve in Finnish and Scandinavian markets, where it is more profitable to replace fossil fuels in heat production. Thus, the first commercial applications for the Novel gasifier in Finland will most likely be in district heat alone production. Better market opportunities for high-efficiency small-scale electricity-from-biomass systems can be found in countries, where the electricity price is higher and/or the biomass-based power is more subsidised.

4. Exploitation plans

Condens Oy and VTT are planning to commercialise the Novel gasifier first in district heating applications in Finland. VTT and Dr. Ilkka Haavisto (owner of Condens Oy) jointly own the rights for the process, and the technology is licensed to Condens Oy. The plan is start the construction of the first demonstration plant (roughly 5 MW) in 2000. Simultaneously, gas cleaning R&D will be continued firstly at the pilot plant located at VTT and then in a slip stream of the demonstration plant. This work will be focused on two applications: a) utilisation of refuse-derived fuels in small-scale heating plants and b) development and demonstration of the gas cleaning concept for engine use. The process is planned to be ready for fully industrial-scale demonstration projects for different applications according to the following timetable:

- Heating applications with clean biomass fuels: early 2000
- Heating applications with refuse-derived fuels: early 2001
- Engine applications: 2002 (after completing the long-term catalyst tests)

The Italian partners, Finesport and Antiche Terre will also study potential sites and markets for building a demonstration plant in Italy based on the new Novel gasification technology. In addition, they are looking for possibilities to move the existing downdraft gasification plant to a suitable site, where it could be used for producing electricity from local wood residues.

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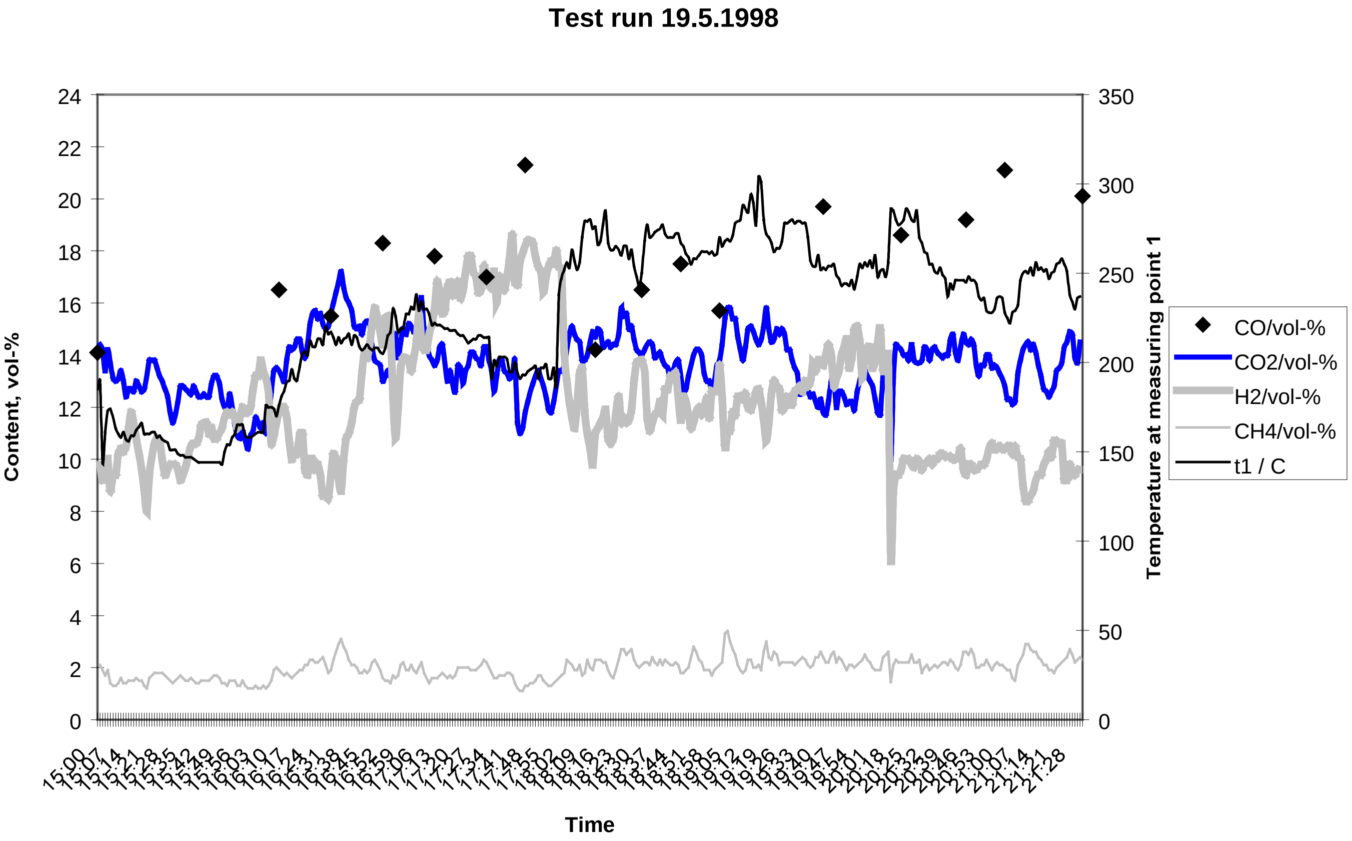
Appendix:

An example of the gas composition and temperature for the downdraft gasification tests carried out with design wood.



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Title

Development of novel fixed-bed gasification for biomass residues and agrobiofuels

Abstract

The project concerned three different approaches to achieve reliable operationin fixed-bed gasification of available biomass residues. The first approach was based on the pretreatment of fuels for use in standard downdraft gasifiers. The second one was based on using a commercially available updraft fixed-bed gasifier for heating applications. The third was based on the developmentg of a new type of gasifier that were independent of the natural descending fuel flow caused by gravity.

The downdraft gasification tests were carried out in Italy in a gasifier-engine-generator facility with a range of Italian biofuels, the aim being to create criteria for fuel selection, collect reliable performance data with suitable fuels and to identify technical possibilities for broadening the feedstock basis by using mixture fuels and additives. The test results and experiences clearly demonstrated the limitations of this type of commercial gasification technology.

Operation experiences of commercial updraft gasifiers operating in Finland and Sweden were collected and evaluated. These updraft gasifiers operate well with sod peat and wood chips. However, these gasifiers cannot operate reliably with low-bulk density fibours fuels like bark, sawdust and shavings.

The third technical approach was realised by designing, constructing and testing a pilot plant of a new type of gasifier, based on forced fuel flow and suitable for low-bulk-density fibrous biomass fuels. The pilot plant was connected to a secondary catalytic gas cleaning device, which made it possible to produce tar-free gas suitable for engine use. This new fixed-bed gasifier makes it possble to utilise such biomass residues and energy crops that cannot be used in the presently available fixed-bed gasifiers, like forest residue chips, sawdust and crushed bark. However, further work is required to demonstrate the whole gasifier, gas cleaning and engine concept and to define the lifetime and availability of the catalytic gas cleaning system.

Keywords
biomass, residues, gasification, packed beds, reactors, reliability, feedstock, Bioneer, gas cleaning, feasibility

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