Innovative Components for Decentralised Combined Heat and Power Generation from Biomass Gasification (INCOM)

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Abbreviations and Acronyms

BMEP	Brake Mean Effective Pressure
DC	Direct Costs
FCI	Fixed Capital Investment
HTL	Technical high school
JAG	Jenbacher AG
LDU	Laboratory Development Unit
LHV	Lower Heating Value
KTH	Kungl Tekniska Högskolan
PEC	Purchased Equipment Costs
STDm^3	Volume related to standard environmental conditions (T_u, p_u)
TCI	Total Capital Investment
TDH	Transport Disengaging Height

1 Specified Objectives

The objective of this project was to enhance the technical and economical viability of small up to medium sized (1.0 to 2.5 MW power output) decentralised biomass CHP units basing on the combination of gasification technology and gas engines which are designed for rural areas in Europe and developing countries. The project was designed for a clear assessment of two different gasification technologies (pressurised air blown and pressurised steam blown fluidised bed gasification) against a wide spectrum of operating conditions which meant a temperature range of 700 to 925°C and a pressure range of 0.5 to 1.0 MPa. Three different kinds of biomass were considered (birch, salix and crushed pelletised straw). Main goal of the project was to minimise the impurities (condensable tar and dust) of the gas up to 50 mg/STDm³ in order to receive a suitable gas for a gas engine. Furthermore, a robust gas engine was designed and adapted for direct utilisation of the biomass fuel gas generated. The experience gained from the test runs were used for engineering of highly integrated gasification unit consisting of an allothermal steam blown pressurised fluidised bed gasifier (2.5 MW_{th}) and a lean engine at an economical size in the range of 1.0 to 1.5 MW power output. The project was divided into three work packages. 1) Gas quality optimisation, 2) Gasifier component optimisation and 3) Gas engine optimisation.

Gas Quality Optimisation

In the "Gas Quality Optimisation" gasification tests were carried out considering three different kinds of biomass (birch, salix and straw pellets) in combination with four different bed materials (silver sand, olivine sand, magnesite and dolomite) at a test gasifier of laboratory scale. The gasification temperature was varied from 700 to 900°C at two pressure levels, 5 and 10 bar. The main objective was the clear assessment between the different gasification technologies, pressurised air-blown and advanced steam-blown fluidised bed gasification. As benchmark parameter for this investigation the impurities (condensable tar and dust) and the hydrogen content of the syngas were chosen, due to the importance of these parameters for the gas engine.

Gasifier Component Optimisation

The objective of the "Gasifier Component Optimisation" was the optimisation of an allothermal steam-blown gasification unit at an economical size with respect to the results gained from the experiments of the "Gas Quality Optimisation". The gasifier was optimised by thermodynamic laws and the system components were adapted to each other to obtain a good overall heat integration. To achieve a high efficiency the process was optimised thermodynamically and thereafter economically by simplification of the system.

A suitable biomass feeding system was tested. A pre-design of the gasifier and further components was made. Therefore, the test gasifier was scaled-up and the scaled gasifier was optimised.

Gas Engine Optimisation

Fuel gas from biomass gasification with a net calorific value of approx. 5 – 10 MJ/Nm3 is to be burned in a highly efficient and environment benign combustion engine. There are two reasons why such a project causes major problems: first, because biomass gas contains amounts of tar substances , and second, because it has high hydrogen content. The condensation temperature of these tar substances is approx. 140°C or less, which means that the temperature should not drop significantly during the charging process. The hydrogen content causes on the one hand high security risks and on the other hand engine knock problems. In order to optimise the operation of the engine the following specific objectives have to be addressed: 1) Definition of gas quality requirements for the gasifier in particular regarding tar content, pressure and gas temperature and 2) optimisation of a 0.7 MW gas engine to operate at temperatures above the condensation temperature range of tar by direct connection to the gasifier, only with a simple gas cleanup system (e.g. cyclone, filter) in between. Utilisation of pressurised gasifiers allow direct injection of the fuel gas into the gas engine by saving turbo equipment for charging the engine.

A further objective of the project was to develop a suitable concept for combustion of pyrolysis gases in gas engines. Due to the pressure and temperature it made sense not to mix the gas with intake air before the turbocharger, as was previously done, but rather as close as possible before the cylinder or directly in the combustion chamber. The TU-Graz had the task of supporting Jenbacher AG with thermodynamic calculations and, on the other hand, the aim was to conduct initial experiments with a newly developed cylinder head in the Institute’s own single-cylinder research engine.

1.1 Background and Role of the Project Partners

University of Essen,TEE, Germany

Contribution

The University of Essen, TEE acted as contract co-ordinator. The gasification tests were performed in close co-operation with the Kungl Tekniska Högskolan (work package "Gas Quality Optimisation"). Moreover, the work package "Gasifier Component Optimisation" was carried out and a concept for an optimised gasification unit was set-up. A technical consultant assisted in the design of the gasifier.

Company Profile

The chair "Technik der Energieversorgung und Energieanlagen" (Technology of Energy Supply Systems and Energy Conversion Plants) is part of the faculty "Maschinenwesen" (mechanical engineering). The faculty is involved in the education of students in mechanical engineering and responsible for graduate and postgraduate studies in energy engineering and chemical engineering (degrees bestowed by the faculty: "Dipl.-Ing." and "Dr.-Ing."). Relevant research work related to the problem area of the proposed JOULE project such as flue gas clean-up, purification of high temperature combustion gas at elevated pressure, fluidised bed combustion, analysis of air pollution from power plants, gas scrubbing and stripping, thermo-economic analysis of co-generation, thermohydraulics of district heating networks, economy of electricity generation, rational use of energy, heat pumps, combustion of methanol in gas turbines, thermodynamics of IGCC and other topics are conducted by the faculty.

The University of Essen, TEE contributed to the JOULE II Projects -CT92-0185 and -CT92-0158 and the JOULE II Extension projects -CT93-0431 and -CT94-0454 as well as to JOULE-THERMIE Projects -CT95-0018 and -CT95-0004.

Jenbacher AG, Austria

Contribution

Jenbacher designed and optimised components of the gas engine for utilisation of hot fuel gases. The engine components were pre-tested at Jenbacher laboratories and at TU Graz.

Company Profile

Relevant research and develop areas: 1) design and development of gas and diesel engines, 2) development of new exhaust after-treatment system like SCR and thermal reactors and 3) development of electrical equipment to control gas and diesel engines.

Technical University Graz, Austria

Contribution

The University Graz will work in close co-operation with Jenbacher. It will carry out the theoretical work and modelling necessary for the optimisation of the gas engine. These results are basic information for Jenbacher according to further improvement of the engine.

Company Profile

The Technical University Graz, Institute for Internal Combustion Engines and Thermodynamics has a staff of 75 persons. Relevant Research Main Areas: 1) thermodynamics, 2) working process within internal combustion engines, 3) engine development, 4) metrology and 5) engine emissions.

Kungl Tekniska Högskolan - KTH, KEM TEK, Sweden

Contribution

KEM TEK contributed to the proposed work with the operation of the pressurised gasification test plant for the required tests, the overall assessment of the test plant performance under various operation conditions and after the use of additives, the analysis of experimental data, the supply of data and test reports concerning the overall plant performance during the tests

Company Profile

The gasification group has been carrying out research in this field for more than twenty years. This group is part of the Department of Chemical Engineering and Technology / Chemical Technology, Kungl Tekniska Högskolan. The Department is concerned with research and education in chemical technology, in particular process chemistry, chemical reaction engineering and system optimisation. This research work is directed towards chemical conversion of energy and matter. Fields of particularly intense research and development are: the chemistry and technology of biofuels and fossil fuels, electrochemical energy technology, process analysis, as well as catalysis and catalytic processes.

The gasification group has participated recently in various EC projects: Joule 2, JOU-CT92-0128, (01 JAN 93 – 31 DEC 94); APAS, Gasification, COAL-CT92-0001, (01 JAN 93 – 31 DEC 94); APAS, Combustion, COAL-CT92-0002, (01 JAN 93 – 31 DEC 94); AIR, AIR2-CT93-1760, (01 JAN 93 – 31 DEC 95); AIR, AIR2-CT93-1436, (01 JAN 93 – 31 DEC 95); Joule 2 Extension, JOU2-CT93-0431, (01 JAN 94 – 31 DEC 96); Joule 2 Extension, JOU2-CT93-0331, (01 JAN 94 – 31 DEC 96); Joule/Thermie, JOR3-CT95-0021 (01 JAN 96 – 31 DEC 97); Joule/Thermie, JOR3-CT95-0053 (01 JAN 96 – 31 DEC 98); Joule/Thermie,

JOF3-CT95-0018 (01 JAN 96 – 31 DEC 98); Joule/Thermie, JOR3-CT97-0125 (01 MAY 97 – 31 APR 99)

2 Scientific and Technical Description

The results from the gasification tests are summarised in chapter 2.1. In chapter 2.3 the required changes for the use of syngas in the gas engine are depicted under consideration of the results regarding the mixture formation process (chapter 2.4). The investigation on the gasifier and the pre-design are described in chapter 2.5. The results from the biomass feeding tests are shown in chapter 2.6. Finally, in chapter 2.7 the concept for the allothermal gasification unit is presented.

2.1 Gas Quality Optimisation

In Work Package 2, gas quality optimisation, the main objective was the clear assessment of the two different gasification technologies, pressurised air blown and advanced steam blown fluidised bed gasification. As benchmark parameter for this investigation the impurities (condensable tar and dust) and the hydrogen content of the syngas were chosen, due to the importance of these parameters for the gas engine.

2.1.1 Test Equipment and Measurement Methods

The biomass gasification tests were performed in a laboratory development unit (LDU). The pressurised fluidised bed reactor with the connected high-temperature filter is shown in Figure 2.1-1. Several reconstructions have been made to give today’s design with a maximum operating pressure of 3.0 MPa. The LDU was constructed for a feeding rate of up to 15 kg/h biomass fuel using different kinds of fluidising and gasifying agents such as air, steam and/or carbon dioxide. The maximum temperature is 1000°C for the reactor and

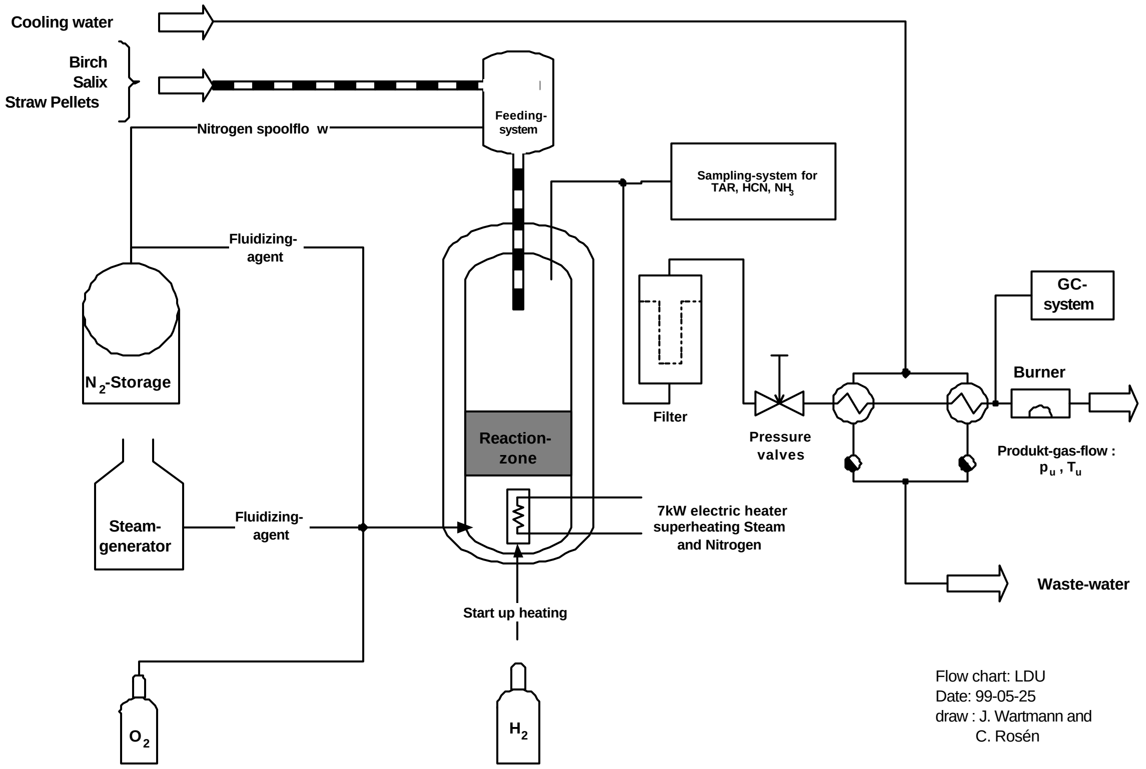


Figure 2.1-1 Scheme of the laboratory developmant unit (LDU)

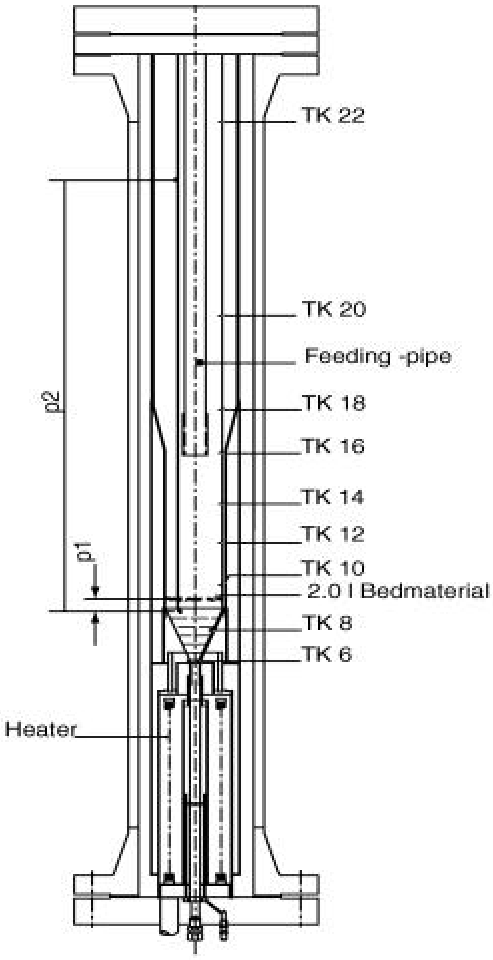


Figure 2.1-2 Reactor of the LDU

500°C for the filter. The fuel hopper and feeder has a fuel capacity of 120 litres.

The reactor is fed from the top directly into the fluidised bed through a cooled and insulated pipe. The 1.5 meter long reactor consists of two different zones, the reaction zone at the bottom and the freeboard in the upper part (Figure 2.1-2). The diameter of the reaction zone and of the freeboard are 0.144 m and 0.2 m, respectively. The inner reactor wall and the bottom which is designed like a perforated cone are made of Inconel steel. The reactor temperatures and pressure drops are continuously monitored. Thermocouples measure the temperature at nine levels and the pressure drops in the bed and over the whole reactor are controlled by pressure pipes. The pre-heated fluidising agents pass through the perforated cone and fluidise the bed material. The syngas exits the reactor at the top and is transported via a heated pipe to the filter. In the high temperature filter the syngas is cleaned from ash and char dust particles by three 1 m long Inconel steel tube socks that are heated to prevent condensation of volatiles and tar. The pressure valve is the last heated part, placed after the secondary reactor, before the syngas is cooled in two water coolers at atmospheric pressure. Most of the tar and the produced water are condensed in the two water coolers. The remaining aerosols are trapped in two 5 µm filters. The analysis of the syngas is made with a gas chromatograph, connected on-line with analyses every ten minutes.

The sampling for tar and nitrogen compounds was taken after the reactor and before the filter during about one hour, at stable test conditions. A conduit of syngas, split into two lines, supports the tar and nitrogen compounds sampling. A new device for the tar sampling based on solid-phase adsorption, SPA (Figure 2.1-3), was used in parallel to water-cooled condensers and cyclone-shaped dry ice traps. For trapping the nitrogen compounds, ammonia and hydrocyanide, the product gas was led through bubble bottles with sulphuric acid and sodium hydroxide, respectively. The total sampling flow was around 3 l product gas per minute. The NO analysis is made on-line beside the gas meter; the NO analysis is made with a chemiluminescence analysis method.

Up to now there is no exact scientific definition of the term “tar” as by-product from a biomass gasification process. The scientific discussion is not finished yet. For the evaluation of the test results the tar content was split into two fractions: “light tar” (GC analysable) and “heavy

The GC analysable tar has a molecular weight from >78 to 300 g/mol. This means that benzene was excluded from the tar content and included in the syngas. The “light tar” could

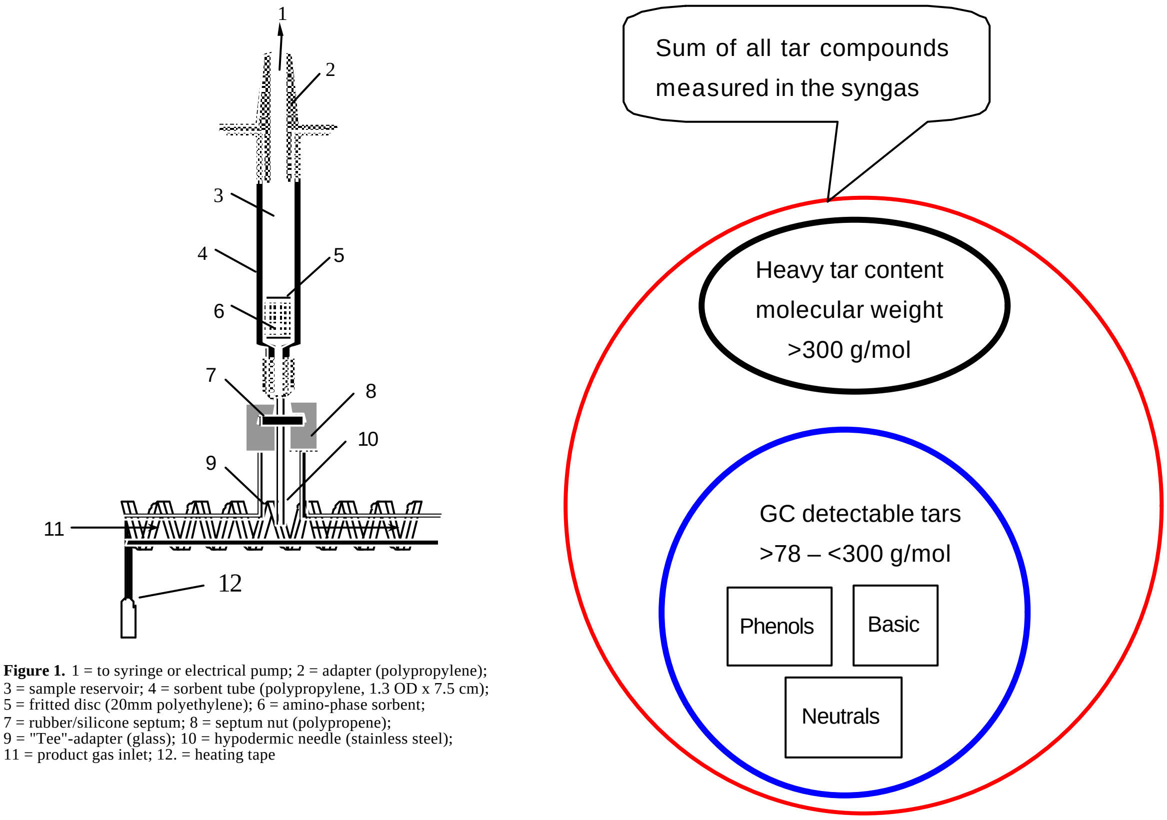


Figure 1. 1 = to syringe or electrical pump; 2 = adapter (polypropylene); 3 = sample reservoir; 4 = sorbent tube (polypropylene, 1.3 OD x 7.5 cm); 5 = fritted disc (20mm polyethylene); 6 = amino-phase sorbent; 7 = rubber/silicone septum; 8 = septum nut (polypropene); 9 = "Tee"-adapter (glass); 10 = hypodermic needle (stainless steel); 11 = product gas inlet; 12. = heating tape

Figure 2.1-3 SPA sampling equipment and overview over the principal tar composition

be divided into three groups of molecules: neutrals, basics and phenolic compounds, as can be seen in Figure 2.1-3.

The determination of the heavy tar fraction from the total tar was performed as follows. As a first step the collected tar sample was taken out from the trap and the trap was cleaned with dichlormethanol to be sure that all tar was taken out. Then the sample was dried at 78 - 83 °C under low pressure to evaporate the dichlormethanol as well as the solved water. At last the sample was determined by a gravimetric method. To be a sure that all “light tar” components were evaporated an extra SPA sample was taken from the trapped tar and analysed separately. Finally the heavy tar content of the syngas was calculated by subtraction of the “light tar” fraction of the trapped tar sample.

The “light tar” was determined directly from the SPA samples that were taken during the test run. The analysed compounds are given in Table 2.1-1. The basic compounds were not analysed since it is known from previous experiments that their amount is very low under the experimental conditions used here.

The ammonia is analysed using an ISE (Ion Selective Electrode) and hydrocyanide is quantified by a wet chemical procedure, but hydrocyanide was below detection level. The syngas flow was analysed every 10 minutes in an on-line gas chromatograph. Analyses of are made of CO_2, H_2, Ar, N_2, CH_4, CO, C_2H_2, C_2H_4, C_2H_6 and hydrocarbons up to C_7.

Table 2.1-1 Measured chromatographable tar compounds

Neutrals	Empirical formula	Phenols	Empirical formula
Toluene	C_7H_8	Phenol	C_6H_6O
m-/p-Xylene	C_8H_{10}	o-Cresol	C_7H_8O
o-Xylene		m-Cresol	
Indene	C_9H_8	p-Cresol	
Naphthalene	$C_{10}H_8$	2,3-Xylenol	$C_7H_{10}O$
2-Methylnaphthalene	$C_{11}H_{10}$	2,4-Xylenol	
1-Methylnaphthalene		2,5-Xylenol	
Biphenyl	$C_{12}H_{10}$	2,6-Xylenol	
Acenaphtylene	$C_{12}H_8$	3,4-Xylenol	
Fluorene	$C_{13}H_{10}$	o-Ethylphenol	$C_8H_{10}O$
Phenanthrene	$C_{14}H_{10}$		
Anthracene			
Fluoranthene	$C_{16}H_{10}$		
Pyrene	$C_{16}H_{10}$		

2.1.2 Procurement and Preparation of the Biomass Tests

The three biomass fuels available for this project, straw pellets, Salix and birch, were supplied as chips or pellets. The chipped fuels, birch and Salix, still had a high moisture content when they were delivered and therefore they had to be dried before further treatment. The drying procedure for the chips was made in two steps: oven-drying at 105 °C followed by an open storage (seasoning) to reach equilibrium moisture content with the surrounding atmosphere. Too high fuel moisture content impacts the fuel flow quality negatively during the course of feeding. After drying the biomass was milled and sieved, through which the fraction of particle size 1.0-3.2 mm is obtained. Figure 2.1-4 shows a picture of fresh chopped birch (left), milled and sieved birch (middle) and pyrolysed birch (right).

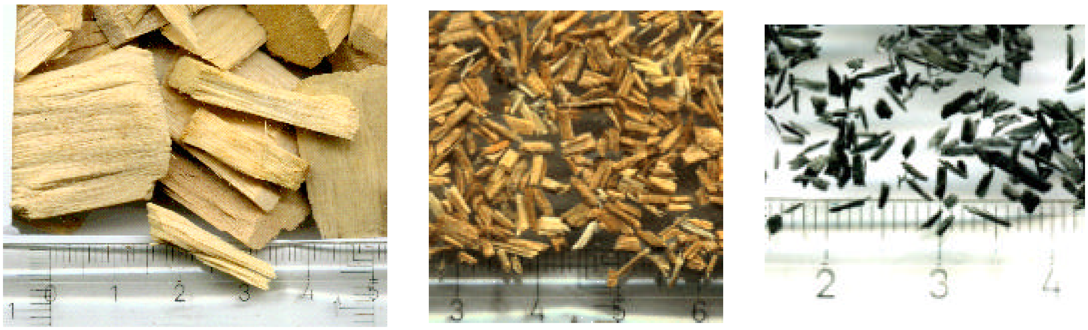

Fresh chipped birch Milled and sieved birch Pyrolysed birch

Figure 2.1-4 Precured and preparated biomass

The top-fed LDU reactor demanded a high precision in selection of the particle size of both bed material and fuel as well as a suitable gas velocity. Well-harmonious conditions in the fluidised bed guarantees a good mixing behaviour without separation problems, with sinking or floating char. The characterisation of the biomass fuels is shown Table 2.1-2, Table 2.1-3 and Table 2.1-4.

Table 2.1-2 Ultimate analysis of the different biomass fuels

Raw Material	C (%wt mf)	H (%wt mf)	N (% wt mf)	O (% wt mf)	S (% wt mf)	MJ/kg (HHV, maf)
Straw pellets	45.4	6.1	1.7	38.86	0.24	19.1
Salix	50.0	5.9	0.7	41.75 (calc)	0.05	19.2
Birch wood	49	6.1	<0.2	44.4 (calc)	< 0.1	19.3

mf: moisture free; maf: moisture and ash free

Table 2.1-3 Proximate analysis of the different biomass fuels

Raw Material	Moisture (% wt)	Fixed carbon (% wt)	Volatiles (% wt)	Ash (% wt mf)
Straw pellets	12*	11.9	80.4	7.7*
Salix	8.6*	14.-9	82.6	1.6*
Birch wood	7*	n.a.	n.a.	0.2*

Table 2.1-4 Trace impurities of the different biomass fuel

Raw Material	Na (% wt mf)	K (% wt mf)	Ca (% wt mf)	Si (% wt mf)	Cl (% wt mf)
Straw pellets	n.a.	n.a.	n.a.	n.a.	0.31
Salix	0.005	0.30	0.40	0.001	0.01
Birch wood	n.a.	n.a.	n.a.	n.a.	n.a.

*average of analyses

2.1.2.1 Used Bed-Materials

At the beginning of this project three different bed materials, silver sand, magnesite and dolomite were chosen. Magnesite and dolomite have the possibility to lower the tar content in the syngas by catalytic tar cracking. An important property of the used bed materials is their resistance against sintering and agglomeration effects, these endanger a stable operation of the gasifier.

Figure 2.1-5 Melted bed material from a steam test at 10 bar, silver sand, Salix at 700°C

The main disadvantage of silica-based bed materials is their sintering behaviour. The strength of the sintering tendencies was mainly influenced by three different parameters: 1) Temperature, 2) pressure and 3) potassium content in the ash.

The potassium traces in the ash lower the melting point of silca based bed-materials depended on their concentration in a fluidised bed. For example Figure x shows sintered bed material in a picture from a scanning electron microscope. The white area in the middle shows melted material, the gray surrounding material is silver sand. Other trace impurities of the ash may also have an impact on the sintering behaviour. However, the whole phenomenon is scientifically not clarified yet and so operational parameters were chosen very carefully.

In addition dolomite is limited in another way, besides lower physical strength. At higher carbon dioxide partial pressures (depending on temperature) dolomite is recarbonised, so the tests with dolomite are limited to a low pressure (maximum 0.4 MPa).

Due to the fact that during the steam tests agglomeration occurred with dolomite and magnesite, another bed material, olivine sand, was used. Olivine sand is known for its good resistance against sintering, but has the disadvantage of a high compact density. Olivine sand is a silica sand with a high MgO content. Additionally, the iron oxide content has an extra catalytic effect. The strength of the catalytic effects is possibly:

$$CaO > MgO > FeO + Fe_2O_3 > SiO_2$$

An overview of the used bed materials is given in Table 2.1-5.

Table 2.1-5 Composition of the bed materials

Material	MgO	SiO_2	$FeO + Fe_2O_3$	Al_2O_3	CaO	Compact density kg/m^3
Silver Sand	-	98.4	-	-	-	2800
Magnesite	84.4	3.9	3.1	0.3	7.5	2600
Dolomite	38.3	2.2	0.5	0.1	58	1450
Olivine Sand	47 - 48	42 - 43	8	1.0	0.5	3300

2.1.3 Pre - tests in the LDU

The performed pre-test pointed out that two reactor thermocouples for bed temperature measurement in the reaction zone were damaged and that the main valve which controls the system pressure was almost plugged. This maintenance work on the equipment was completed. During the maintenance some reconstruction was done inside the reactor to make it possible to add oxygen in the upper part (freeboard) of the reactor. The steam generator was approved by the pressure vessel authorities. The secondary water cooler was repaired and tested. The feeding system was tested on the three available biomass fuels and worked well without any disturbances.

2.1.4 Overview of the performed air gasification tests

In total 40 air gasification tests were performed at the bench scale equipment. Tests covered the planned ranges for the temperature (700 - 930°C), pressure level, bed material and the different kinds of biomass. Table 2.1-6 shows an overview of the performed tests.

The emphasis of the performed tests was on the lower pressure level and on the full spectrum of the proposed temperature range. With the parameter combination Salix as biomass, 900°C, 5 bar, five tests were performed. Incom 23 was a test with a very high temperature, 950°C. During Incom 22 we added a small amount of steam to perform an air with steam run, to maximise the hydrogen content. The other tests with the same setup are repetitions of previous test to verify the results. Due to the fact that the gas engine needed only 3 bar at the inlet to combustion chamber and to avoid sintering most of the test were performed on the lower pressure. It could be deduced that the higher pressure level does not increase the syngas quality.

Table 2.1-6 Overview of the performed “air“ tests

Air gasification tests								
			Temperatures					
			700 °C		800 °C		900 °C	
			Pressure		Pressure		Pressure	
		Bed materials	5 bar	10 bar	5 bar	10 bar	5 bar	10 bar
Biomass	Birch	Silver sand	Incom 19	No promising results expected	Incom 16			
		Magnesite	Incom 18		Incom 15;17		Incom 11, 13, 14	Incom 12
		Dolomite	Incom 35		Incom 36	No catalytic effect	Incom 37	No catalytic effect
		Olivine sand						
	Salix	Silver sand	Incom 10		Incom 7	Incom 8	Incom 5	Incom 6
		Magnesite	Incom 9		Incom 3	Incom 4	Incom 1	Incom 2
		Dolomite	Incom 25,28		Incom 26,29	No catalytic effect	Incom 21, 22, 27, 30	No catalytic effect
		Olivine sand	Incom 31		Incom 32		Incom 24, 33	
	Straw pellets	Silver sand				Sintering expected		Sintering expected
		Magnesite						
		Dolomite			Incom 20			
		Olivine sand	Incom 38		Incom 39		Incom 40	

2.1.5 Overview of the performed steam tests

All 20 steam tests were performed mainly at a low pressure level, because the scale up predicts better system efficiencies. A higher pressure will increase the steam mass flow significantly. The pure steam tests were performed between 700 – 800 °C, because the heat exchanger in the pilot gasifier of the CHP unit was limited to this temperature level. An overview oft the performed tests are given in Table 2.1-7.

2.1.6 Evaluation policies of the performed tests

To assess the two different gasification technologies, fluidised pressurised air-blown and advanced allothermal steam-blown gasification two different kind of parameters were used:

- Direct parameters:
  The raw data from the tests were recalculated to average values that are connected to the tar sampling period (about one hour).
- Standardised parameters:
  By relating the obtained values to the fed biomass, the dilution and concentration effects

Table 2.1-7 Overview of the performed steam tests

			Steam gasification tests					
			Temperatures					
			700 °C		800 °C		900 °C	
			Pressure		Pressure		Pressure	
		Bed materials	5 bar	10 bar	5 bar	10 bar	5 bar	10 bar
biomass	Birch	Silver sand		IncS 10	IncS 1,2,3,4			
		Magnesite						
		Dolomite			IncS 12			
		Olivine Sand	IncS 19				IncS 20	
	Salix	Silver sand		IncS 9,11				
		Magnesite		IncS 7,8,	IncS 6,5			
		Dolomite						
		Olivine Sand	IncS 16		IncS 17, 18			
	Straw pellets	Silver sand			Sintering likely			
		Magnesite						
		Dolomite	IncS 13,14					
		Olivine Sand	IncS 15					

from the gasification agent could be excluded. The standardised parameters were used to clarify and support the direct parameters.

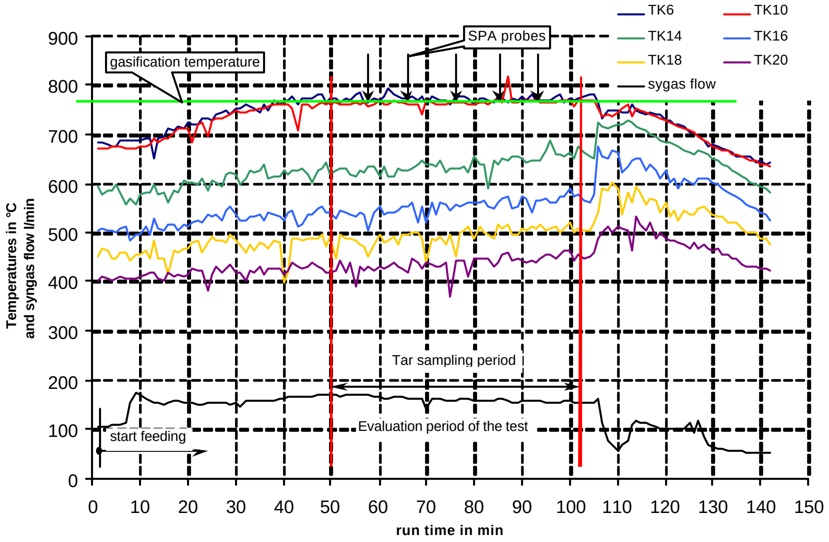
The nitrogen content of the air tests was corrected to level that resulted from the feed oxygen content. All syngas compositions were recalculated to dry values and in addition the results from the steams runs are shown nitrogen free.

Figure 2.1-6 shows as example recorded data from a steam test to clarify the above-described procedure. The graph shows a temperature profile and the measured syngas flow during IncS18. Additionally the scheme of the LDU shows where the thermocouples are placed inside the rector.

The biomass fed during this period was calculated backwards from the syngas composition and the measured tar content, so that fuel flow is moisture and ash free. This suppresses uncertainties of the feeding system. Table 2.1-8 shows typical results from the three different obtained feed flows of some tests.

2.1.7 Comparison of the obtained gas compositions

As described above the emphasis of the gasification tests is the maximisation of the hydrogen content. The hydrogen content is an important parameter for the gas engine and its combustion process.



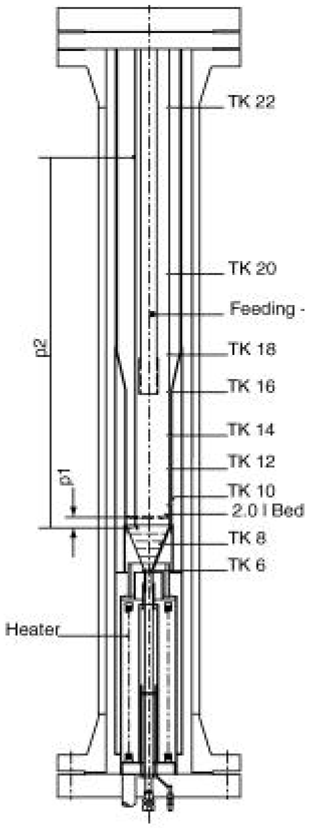


Figure 2.1-6 Recorded temperature profile of the LDU (IncS 18)

Table 2.1-8 The different feeding flows for some tests.

Test name	Calibrated feed flow in kg/h	Recalculated feed flow in kg/h	Average feed flow in kg/h
Incs 20	7.13	9.12	6.58
IncS 19	3.20	6.09	5.00
IncS 18	2.83	2.96	2.88
IncS 12	1.06	1.14	1.27

In Figure 2.1-7 the obtained syngas qualities of some typical air gasification tests are shown. To compare the obtained results a composition of two steam tests and published data from another test rig, at TPS (Termiska Processren Studsvik) are also shown.

For air gasification a hydrogen content of about 11.5 %vol was reached at a high gasification temperature, compared to about 40 %vol of the steam tests and 25 %vol of steam tests with admixed air.

Also compared to the results from TPS the reached hydrogen contents were lower. This could be explained by differences in the gasifier concept. The shown syngas composition from TPS included a dolomite tar cracking device. As results of the tar cracking process the hydrogen and CO_2 contents increase. The TPS system is a fast fluidised bed which needs more air for the fluidisation and also a secondary air inlet for the tar cracker; from this follows an increased nitrogen content of the syngas. Overall, it could be pointed out that there were no major differences in the fuel gas composition between the TPS gasifier and the LDU, if taken into account that the tar cracker as second gasification step has positive influence on the hydrogen content.

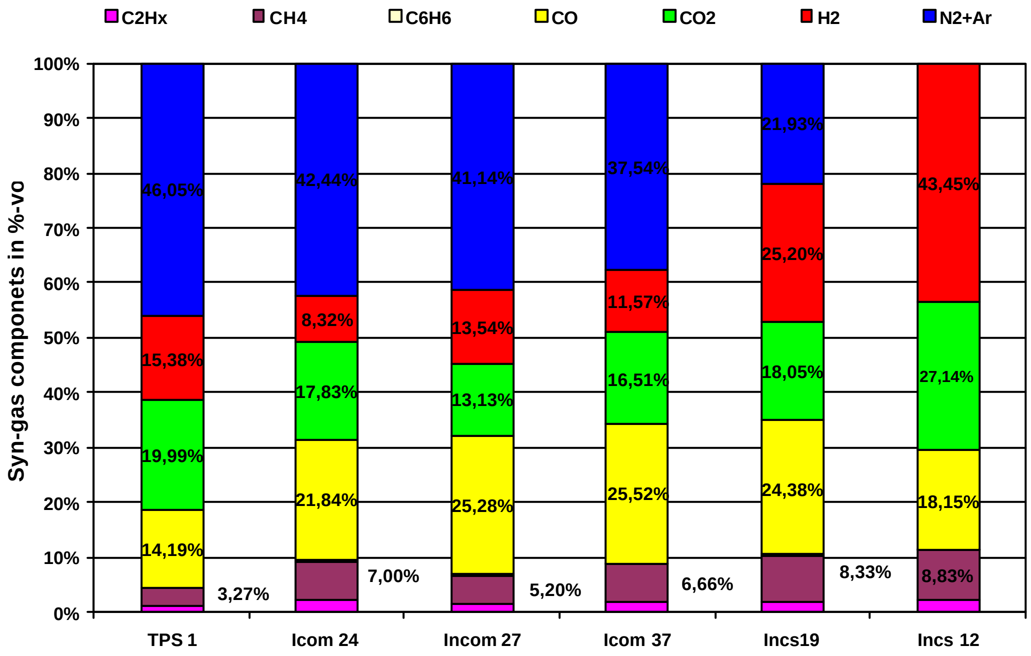


Figure 2.1-7 Obtained syngas qualities from different air tests compared to three references

It could be confirmed that with steam or steam/air gasification much higher hydrogen contents could be obtained. This is also supported by other obtained results, which are in the tables at the end of this chapter.

However, a question is whether the positive results for steam gasification are reached through condensation of the gasification medium or if the gasification mechanism is responsible for the reached hydrogen content. To investigate this circumstance the hydrogen produced per kg fed biomass is shown in Figure 2.1-8.

The chart above shows the specific hydrogen yield versus the temperature for both gasification technologies. With both gasification agents the hydrogen content increases with

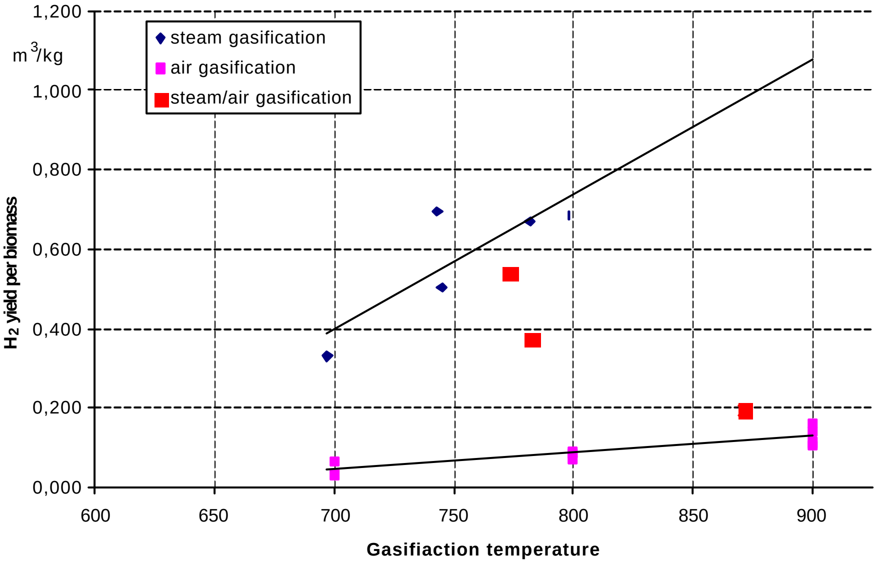


Figure 2.1-8 Hydrogen contents related to the fed biomass

an increase of the gasification temperature. The drawn linear trends indicate a stronger increase of the hydrogen yields for the steam blown gasification, compered the air blown. Unfortunately, the calculated trend could not be proved for the steam gasification at the highest temperature level. The measured results for the steam/air gasification shows that the obtained syngas quality depended on the fed air. However, it should be remarked that with air or air/steam gasification up to 8 times higher feeding rates were obtained, this is an important parameter for the size of a possible gasifier.

2.1.7.1 Obtained Lower Heating Values (LHV)

Different lower heating values (LHV) of the tests are shown in Figure 2.1-9. The highest lower heating values were reached with pure steam tests. Thereby it must be to taken into account that the concentration effects from the condensed steam influence strongly, because the heating values are related to a given volume. With the full steam content which occurred in the fluidised, bed the syngas is not combustible in the gas engine.

In the steam tests an average LHV of about 11 MJ/m^3 could be reached. In tests with both gasification agents a lower heating value of about 9 MJ/ m^3 was obtained and the lowest heating values were measured for the air gasification tests, about 6.5 MJ/m^3. However, it is important to point out that this is high enough to operate the gas engine safely.

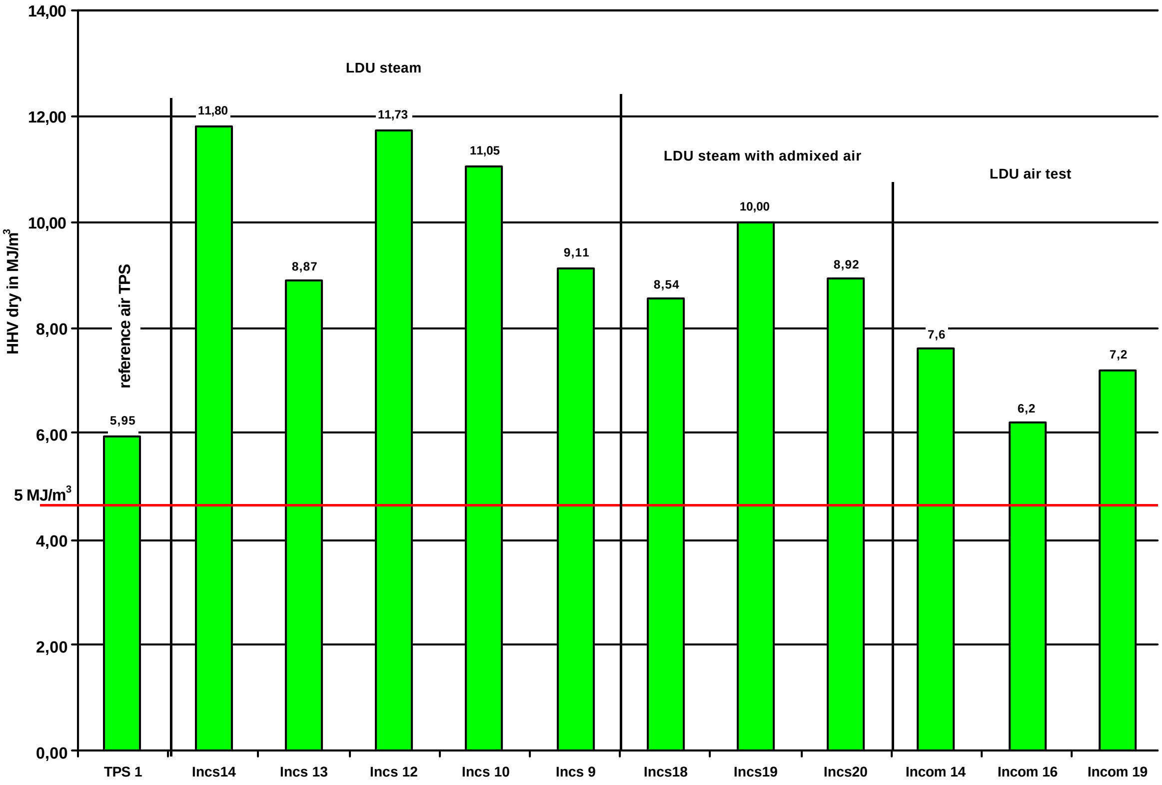


Figure 2.1-9 Heating values of the different gasification technologies

2.1.7.2 Obtained Tar Concentrations in the Syngas

The tar content of the syngas is determined as described in chapter 2.1.6. Given the condensation of the water content in steam gasification and the dilution from the nitrogen content in air gasification a direct comparison of the tar contents as concentrations of the syngas is not reasonable. To compare the obtained results the tar content was standardised to the fed biomass.

The graph (Figure 2.1-10) shows the tar composition of some air tests with dolomite as catalytic bed material at a low pressure level and high temperature, compared to a steam test with a large amount of admixed air and olivine sand as bed material.

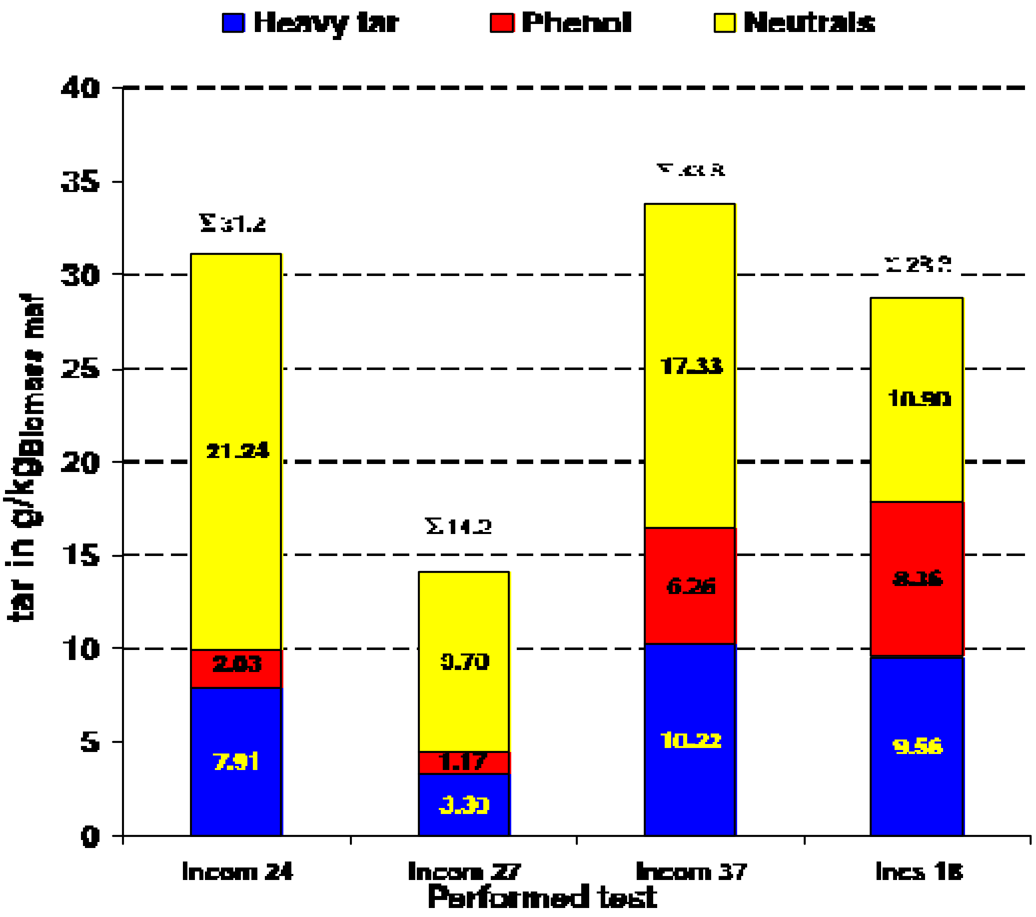


Figure 2.1-10 Tar compositions obtained from the air gasification tests

The lowest tar yields were measured for air gasification with dolomite as catalyst (25 g/kg). Then the tar mainly consists low molecular weight neutral compounds and compered to the steam tests. The high molecular weight compounds are less dominant (< 50%) this has a positive influence on the condensation behaviour, because the condensation temperature will increase. The change of the composition of tar shows that high molecular weight compounds were cracked by the use of high temperature and dolomite as catalyst, but it is to be pointed out that the neutral and phenolic compounds could not cracked under the used experimental conditions. However, the tar content still is too high for direct feeding into the gas engine, so a separate tar cracker is necessary.

The graph (Figure 2.1-11) shows the tar yields reached at the steam tests. The first three results are from steam tests with admixed air, they are followed by results obtained in pure steam tests and the two last results were performed at the high pressure level.

It turned out that with pure steam gasification the highest tar yields were obtained, compared to the other gasification media (air, air/steam; Figure ddd). As shown in Figure ffff the tar composition changes especially from high pressure, low temperature steam gasification to

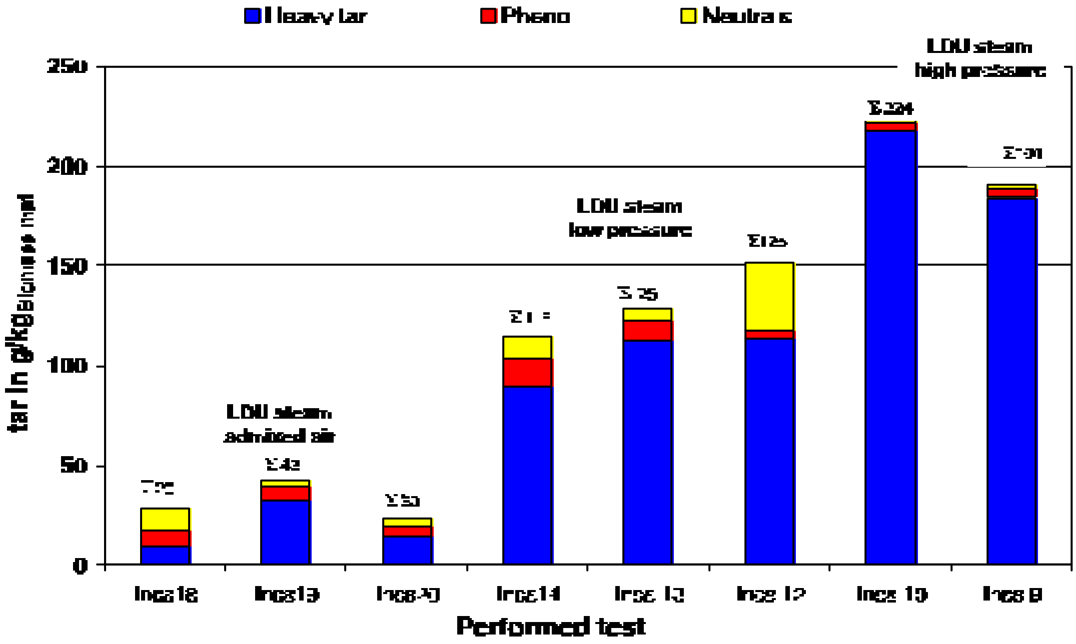


Figure 2.1-11 Tar compositions obtained from the steam gasification tests

low pressure, high temperature air gasification. Under the first circumstances the highest measured tar yields were reached, about 220 g/kg and the tar consisted mainly of high molecular weight compounds. Through the admixing of air into the fluidised bed in the steam gasification tests, the total amount of all tar compounds could be lowered to about 30g/kg. The tar composition itself was unchanged, the high molecular weight compounds were dominant.

2.1.7.3 Detailed data from of all performed tests

At last all results from all tests are summarised in one table to give an overview of all the performed tests.

Test name	**Incom 1**	**Incom 2**	**Incom 3 #**	**Incom 4 #**	**Incom 5**
Pressure in MPa	0.5	1.0	0.5	1.0	0.5
Fuel / particle size in mm	Salix/1-3	Salix/1-3	Salix/1-3	Salix/1-3	Salix/1-3
Bed material	MgO	MgO	MgO	MgO	Silver sand
Bed temperature in °C	900	900	800	800	900
NH_3 in product gas* in ppm	1773	1630	1158	802	1463
NO in product gas* in ppm	14	15	44	21	13
Total tar in g/Nm^3 product gas*	7.5	4.1 1)	30.3	17.3	10.8
Product gas composition* (moisture free)**:**					
N_2	51.2	56.8	50.3	46.9	57.9
CO	19.4	10.9	19.6	22.5	14.6
CO_2	14.7	20.7	17.4	21	14.8
H_2	7.2	5.3	5.6	-	4.4
CH_4	5.7	5.9		8.0	6.4
C_2H_2	1.2	3.0	0.8	0.9	0.1
C_2H_4	0.4	-	0.4	0.6	1.3
C_2H_6	-	-	-	-	-
C_6H_6	0.24	0.4	0.09	0.13	0.49
λ O_2 gasification	0.22	0.23	0.11	0.08	0.24
Product gas* HHV in MJ/Nm^3	6.5	6.3	5.7	6.7	6.1

Test name	**Incom 6 #**	**Incom 7**	**Incom 8**	**Incom 9 #**	**Incom 10**
Pressure in MPa	1.0	0.5	1.0	0.5	0.5
Fuel / particle size in mm	Salix/1-3	Salix/1-3	Salix/1-3	Salix/1-3	Salix/1-3
Bed material	Silver sand	Silver sand	Silver sand	MgO	Silver sand
Bed temperature in °C T8	900	800	800	700	700
NH_3 in product gas* in ppm	1518	1302	1351	287	760
NO in product gas* in ppm	13	16	36	32	74
Total tar in g/Nm^3 product gas*	31.8	23.8	20.8 1)	87.9	7.5 2)
Product gas composition* (moisture free)**:**					
N_2	55.2	57.6	53.1	48.2	64.7
CO	18.4	15.6	18.7	17.5	9.3
CO_2	16.6	17.6	17.7	23.7	15.7
H_2	2.3	2.6	4.0	5.2	3.6
CH_4	5.1	4.2	4.2	3.5	3.9
C_2H_2	0.5	0.5	0.7	0.7	0.3
C_2H_4	1.5	1.3	1.2	1.1	0.6
C_2H_6	-	-	-	-	0.004
C_6H_6	0.54	0.4	0.35	0.09	0.05
λ O_2 gasification	0.26	0.22	0.18	0.09	0.24
Product gas* HHV in MJ/Nm^3	6.2	5.5	5.9	5.2	3.5

*recalculated to air-gasification, # bed disturbances, 1) no phenols analysed

Test name	**Incom 11 #**	**Incom 12**	**Incom 14**	**Incom 16**	**Incom 17 #**
Pressure in MPa	0.5	1.0	0.5	0.5	0.5
Fuel / particle size in mm	Birch/1-3	Birch/1-3	Birch/1-3	Birch/1-3	Birch/1-3
Bed material	MgO	MgO	MgO	Silver sand	MgO
Bed temperature in °C	900	900	900	800	800
NH_3 in product gas* in ppm	33	325	320	217	7
NO in product gas* in ppm	70	37	28	51	57
Total tar in g/Nm^3 product gas*	62.3	23.9	9.9	17	36.4
Product gas composition* (moisture free)**:**					
N_2	40.3	48.1	43.9	55.3	48.4
CO	30.1	17.4	19.8	17.6	26.3
CO_2	12.6	16.6	17.4	15.4	13.5
H_2	8.9	8.4	9.8	3.7	5.5
CH_4	5.3	7.4	6.8	5.8	4.6
C_2H_2	0.8	0.6	0.4	0.3	0.4
C_2H_4	1.7	1.2	1.6	1.6	1.1
C_2H_6	-	0.02	-	-	-
C_6H_6	0.26	0.32	0.34	0.30	0.16
λ O_2 gasification	0.12	0.2	0.18	0.21	0.12
Product gas* HHV in MJ/Nm^3	8.4	7.2	7.6	6.2	6.6

Test name	**Incom 18 #**	**Incom 19**	Incom 21	Incom 22	Incom 24
Pressure in MPa	0.5	0.5	0.5	0.5	0.5
Fuel / particle size in mm	Birch/1-3	Birch/1-3	Salix/1-3	Salix/1-3	Salix/1-3
Bed material	MgO	Silver sand	Dolomite	Dolomite	Olivine
Bed temperature in °C	700	700	900	900	950
NH_3 in product gas* in ppm	5	36	69	305	672
NO in product gas* in ppm	n.d.	13	5.5	9.6	5
Total tar in g/Nm^3 product gas*	22.7	17	5.1	2.8	10.7
Product gas composition* (moisture free)**:**					
N_2	55.0	56.9	48.9	33,7	54.8
CO	14.1	15.6	25.9	19.1	17.6
CO_2	18.9	16.8	13..4	17.4	14.3
H_2	6.9	3.8	6.1	24.7	5.6
CH_4	3.8	4.9	4.1	4.1	5.6
C_2H_2	0.4	0.6	0.9	0.6	1.5
C_2H_4	0.8	1.2	0.6	0.4	0.3
C_2H_6	-	-	-	-	-
C_6H_6	0.09	0.14	0.09	0.06	0.3
λ O_2 gasification	0.13	0.2	0.13	0.15	0.17
Product gas* HHV in MJ/Nm^3	4.7	5.4	6.3	7.1	6.3

*recalculated to air-gasification, # bed disturbances, $^{1)}$ no phenols analysed, $^{a)}$ only chromatographable tar,

Test name	Incom 25	Incom 26	Incom 27	Incom 35	Incom 36
Pressure in MPa	0.5	0.5	0.5	0.5	0.5
Fuel / particle size in mm	Salix/1-3	Salix/1-3	Salix/1-3	Birch/1-3	Birch/1-3
Bed material	Dolomite	Dolomite	Dolomite	Dolomite	Dolomite
Bed temperature in °C	700	800	900	700	800
NH_3 in product gas* in ppm	-	-	915	-	-
NO in product gas* in ppm	1	10	30	2	15
Total tar in g/Nm3 product gas*	0.6a	1.8a	6.4	0.4a	3.5a
Product gas composition* (moisture free)**:**					
N_2	55.4	49.5	51.0	37,9	47.7
CO	13.6	19.2	23.1	13.1	16.5
CO_2	19.0	15.2	5.2	19.4	17.3
H_2	5.8	10.6	14.1	19,4	11.6
CH_4	4.9	3.9	5.0	8.7	5.3
C_2H_2	0.4	0.5	0.4	1.0	0.4
C_2H_4	0.8	1.0	1.0	2.4	1.0
C_2H_6	-	-	-	-	-
C_6H_6	0.08	0.14	0.19	0.29	0.18
λ O_2 gasification	0.19	0.20	0.21	0.19	0.18
Product gas* HHV in MJ/Nm3	4.9	6.0	7.3	9.2	6.3

Test name	**Incom 37**
Pressure in MPa	0.5
Fuel / particle size in mm	Birch/1-3
Bed material	Dolomite
Bed temperature in °C T8	900
NH_3 in product gas* in ppm	141
NO in product gas* in ppm	41
Total tar in g/Nm3 product gas*	13.9
Product gas composition* (moisture free):	
N_2	39.4
CO	23.4
CO_2	15.5
H_2	13.9
CH_4	6.3
C_2H_2	0.4
C_2H_4	0.9
C_2H_6	-
C_6H_6	0.23
λ O_2 gasification	0.17
Product gas* HHV in MJ/Nm3	7.7

*recalculated to air-gasification, # bed disturbances, 1) no phenols analysed, a) only chromatographable tar,

Test name	**IncS 1**	**IncS 2**	**IncS 3**	**IncS 4**	**IncS 5**	**IncS6**	***IncS 7**	**IncS 8**	**IncS 9#**	**IncS 10**	**IncS 11#**
Pressure in MPa	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0
Fuel / particle size in mm	Birch	Birch	Birch	Birch	Salix	Birch	Salix	Salix	Salix	Birch	Salix
Fuel feeding rate in kg DS/h	2.27	3.95	-2)	7,6	4,78	3.6	-2)	2.22	2.10	1.04	1.08
Bed material	Silver sand	Silver sand	Silver sand	Silver sand	Silver sand	MgO	MgO	MgO	Silver sand	Silver sand	Silver sand
Bed temperature in °C	800	800	800	800	800	800	750	750	750	750	750
Total tar in g/Nm^3 product gas	-	-	-	-3)	27.8	2.6*	9.2	6.3	13.9	34.5	13.1
Product gas composition (moisture free)**:**											
N_2	-1)	63.05	-2)	60.50	56.41	57.52	-2)	65.0	79.2	85.4	85.2
Ar	-	-	-	-	-	-	-	-	-	-	-
CO	-	15.88	-	16.67	11.58	7.24	-	3.5	2.5	2.1	1.6
CO_2	-	10.05	-	10.77	13.95	14.89	-	12.1	7.4	4.2	4.3
H_2	-	4.50	-	4.70	14.93	15.18	-	16.8	9.3	6.6	7.5
CH_4	-	5.68	-	5.35	2.94	3.91	-	2.2	1.2	1.3	1.0
C_2H_2	-	1.27	-	1.11	0.40	0.70	-	0.2	-	-	-
C_2H_4	-	0.50	-	0.70	0.24	0.50	-	0.1	0.1	0.1	0.1
C_2H_6	-	-	-	-	-	-	-	-	0.1	0.1	0.09
C_6H_6		0.20	-	0.12	0.03	0,13	-	0.02	0.01	0.01	0.01

1)Error of the GC system; 2) Feeding fault unsuccessful, 3) no tar measurement; *havy tar only; # bed disturbances

Test name	**IncS 12**	**IncS 13#**	**IncS 14**	**IncP 1**	**Incs15#**	**Incs16**	**Incs17**	**Incs18**	**Incs19**	**Incs 20**
Pressure in MPa	0.5	0.5	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.5
Fuel / particle size in mm	Birch/1-3	Straw/1-3	Straw/1-3	Birch/1-3	Straw/1-3	Salix	Salix	Salix	Birch	Birch
Fuel feeding rate in kg DS/h	1.25	2.25	3.10	1.07	1.08	2.1	2.25	3.10	3.02	7.13
Bed material	Dolomite	Dolomite	Dolomite	Silver sand	Dolomite	Olivine sand	Olivine sand	Olivine sand	Olivine sand	Olivine sand
Bed temperature in °C	800	780	740	700-800	700	750-800	780	740	800	800
Total tar in g/Nm^3 product gas	13.6	23,7	28.0	*	1.8	1.4 3)	- 2)	8.8	18.4	16.5
Product gas composition (moisture free):										
N_2	70.0	72.4	71.6	96.7	-1)	-	-	58.26	53.20	49.87
Ar	-	-	-	-	-	-	-	-	-	-
CO	5.0	1.7	3.4	1.7	-	-	-	9.27	14.60	18.95
CO_2	7.2	8.8	8.9	0.4	-	-	-	11.10	10.81	11.32
H_2	14.6	15.4	13.1	0.3	-	-	-	16.28	15.92	9.92
CH_4	2.4	1.4	2.2	0.7	-	-	-	4.03	4.98	7.78
C_2H_2	0.3	-	0.3	-	-	-	-	0.38	0.48	0.47
C_2H_4	0.4	0.1	0.3	0.1	-	-	-	0.54	0.71	1.27
C_2H_6	-	0.1	-	0.05	--	-	-	-	-	-
C_6H_6	0.04	0.01	0.03	0.007	-	-	-	0.08	0.07	0.3

1)Error of the GC system; 2) Feeding fault unsuccessful,3) No datas recored,# bed disturbances

2.1.8 Operational Principles and Conclusion on Gas Qualtiy Optimisation

Based on the experiments described above, a set of parameters for stable operating conditions for both gasification technologies are delivered. The test results show that the highest hydrogen contents were obtained with steam gasification, but with very high tar amounts. The totality of the made gasification tests shows that it is very helpful to admix oxygen to allothermal steam gasification. This enhances the pure steam gasification process in two important ways. It lowers the tar content to values that make the tar cracking more feasible and the fuel throughput is increased. The lowest tar contents were measured in the air gasification tests. The low hydrogen yield of air gasification could be increased through admixing of steam and through the use of a tar cracker. Below an overview for stable operational conditions for all gasification technologies are shown:

For steam gasification:

0.1-0.5 MPa; 750 – 850 °C, olivine sand , all different kinds of biomass with low to medium ash content (woody fuels), straws limited in use, separate tests required. Dry LHV 9-11 MJ/m_n^3 , up to 42 %vol. H_2, 120 g_{Tar}/kg_{Fuel}

For air gasification:

0.1-0.5 MPa; 850 - 950°C, olivine sand, dolomite, all different kinds of biomass with low to medium ash content (woody fuels), straws limited in use, separate tests required Dry LHV 5-8 MJ/ m_n^3 , <10 %vol. H_2, ≈ 30 g_{Tar}/kg_{Fuel}

For air/steam gasification:

0.1-0.5 MPa; 750-900°C, olivine sand, all different kinds of biomass low to medium ash content (woody fuels), straws limited in use, separate tests required. Dry LHV 7-9 MJ/ m_n^3, <15 %vol. H_2, ≈50 g_{Tar}/kg_{Fuel}

2.2 Outlook

The tests have shown that neither of the two assessed gasification technologies meet both requirements of low tar content and high hydrogen content. The best results could be obtained with a mixture of the gasification technologies. With further tests it has to be investigated where the optimal ratio between the gasification media steam and air is to be found and advanced bed material has to be included in the investigation. This optimisation has to be performed under certain boundary conditions: the requirement on the needed syngas quality for the gas engine and the requirements for the gasification process, especially for the tar cracker, so that the gas engine and gasification process can be operated in an environmentally benign manner and economically successfully.

2.3 Adaption of a Gas Engine for Biomass Derived Fuel Gas

2.3.1 Component Detail Engineering and Design

Based on the development and adaptation of gas engine to clean biomass gas (syngas) it becomes necessary to refine some newly designed engine parts for application of hot syngas. In this project the focus lies on the optimisation of the technological performance of engine components.

The main topics to be addressed in the optimisation phase are the following:

- Hot gas blow in valve
- The blow in valve actuating system
- Design of the pre-chamber and the main combustion chamber
- The insulated hot gas gallery
- The preassure regulator working at a temperature value highre than 80°C
- Cylinder liner with high resistance for wear
- Piston rings with high resistance for wear
- Exhaust valves with high resistance for wear

2.3.2 Component construction and modification

To avoid hot spots in the combustion chamber, where syngas with high hydrogen content can start autoignition, a new pre chamber was designed.

2.3.3 Hot gas metering valve

Through the converted concept an already developed gas inblow valve can be used. In coordination with Fa. Hörbiger the valve can be used safely up to a gas temperature of 100°C, for temperatures higher than 100° C the actor would have to be separated from the hot part of the valve and then be connected with a coupling element.

2.3.4 Design studies of the special cylinder head type

Proceeding from the best solution for an internal mixture formation, rooted in the CFD calculations, it was worked on the constructive realization in the scope of a project work at the HTL at Steyr (school for engineers with graduation). To test the cylinder head on the single cylinder research engine resulting from the task the Version C (series production up to 7/1999) was chosen. This design of the cylinder head is similar to the version which is in series right now, concerning the inlet and outlet ports. With that after the successful termination of the experiments the founded solution statement can directly be transferred to the latest cylinder head design.

2.3.5 Cold performance test

The engine optimisation tests are performed at a single cylinder research engine with same bore and stroke dimensions as the full engine at TU Graz VKM for modelling purposes. For security requirements all these optimisations tests at TU Graz VKM was firstly done with could natural gas. The target was to get more information for thermodynamic calculations. The results of the new gas feeding system are good (see TU Graz), this concept can be used for commercial gas engines operating with natural gas as well because it did not reduce the efficiency of the gas engine as the test have shown.

2.3.6 Thermodynamic calculation and modelling

The engine performance optimisation was done in close co-operation with TU Graz. Results from these calculations were used to modify and optimise components of the gas engine.

2.3.7 Definition of gas quality requirements for the gasifier in particular regarding tar content, pressure and gas temperature

- The particular tar content should be lower than 30 mg/Nm^3
- The amount of NH_3 should be lower than 55 mg/Nm^3
- The pressure of the hot syngas should be about 3 bar
- The temperature of the hot gas can be higher than 100 °C

2.3.8 Hot performance tests

To establish the influence of the mixture temperature on the combustion, an experiment was carried out at JAG, which shows the influence of the knocking limit with different methane numbers (MZ) and different mixture temperatures.

Biogas is added first shortly before the inlet valves, due to the mixing of cooled charge air and hot biogas the temperature to be expected is located in the area between about 80°C and therefore in an area which should be executable without problems.

2.3.9 Engine operation with syngas

Experiments with syngas have been carried out at a pilot plant. A 12 cylinder engine was operated with syngas without problems, at a break mean effective pressure (bmep) of 13 bar. The syngas was produced conventionally afterwards thoroughly cleansed. The gas supply was carried out in the same conventional manner by the gas mixer before the turbocharger. The rate of heat realise (ROHR) and the sum heat realise (HR) are shown in Figure 2.3-1.

A quick conversion of the fuel takes place, additionally the running of the engine was very stable. The problem of the plant was according to a lack of gas supply, syngas was available only for periods each of about five hours. Also the gas cleaning is very costly and especially due to the vast amount of polluted water poses a problem. The composition of the syngas was shown in Table 2.4-1.

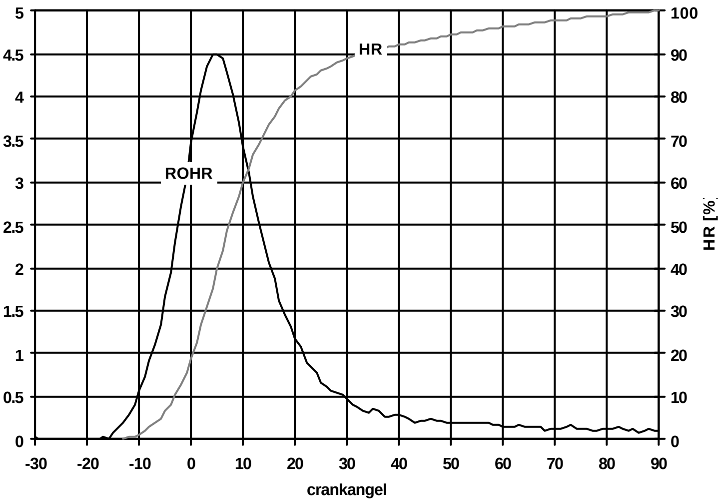


Figure 2.3-1 Rate of heat realise

Table 2.4-1 Syngas Composition

	Unit	Analyse
Calorific value	[kWh/m^3]	1.5
Methan	[Vol%]	4.96
H_2	[Vol%]	13.46
CO	[Vol%]	17.1
CO_2	[Vol%]	17.3
N_2	[Vol%]	47.18
Naphtalin	[g/m^3]	1
Ammoniak	[mg/m^3]	30
Tar	[mg/m^3]	10

2.4 Investigations on a Suitabe Mixture Formation Concept for the Gas Engine

2.4.1 Requirements to be Fulfilled by the Mixture Formation Concept

The task of mixture formation is to provide a homogeneous mixture of combustion gas and intake air at ignition timing. In order to achieve efficient combustion of the gas with a low level of pollutants, the quality of mixing is of decisive importance. Inhomogeneous areas in the combustion chamber cause the concentration of pollutants, primarily nitrogen oxides, to increase. Knock tendency also increases. Furthermore, mixture formation must ensure that an ignitable mixture is available at the spark plug position at ignition timing.

When pyrolysis gases are burnt, there is also the risk of tar deposits collecting on the intake section, thus impairing proper functioning of the engine. As the pyrolysis gas is already at a high pressure of 3 to 7 bar and a temperature of approx. 160 °C, it would not make sense to mix the gas before the turbocharger, as was previously done. It would need to be relieved to ambient pressure, which would entail a loss of energy. Another disadvantage would be that the temperature would fall below the condensation temperature of tar, thus resulting in severe deposits. The greater percentage of hydrogen in pyrolysis gases poses the risk of auto-ignition. Thus, the aim is of the new mixture formation method is to get the pyrolysis gas directly into the cylinder either as close before the intake valve in the intake port or with the aid of a special prechamber-like mixing facility.

2.4.2 Basic Version (Ideal Mixing)

In order to obtain a comparative version for the following variations, a 3D-CFD model was first drawn up on the basis of a so-called basic concept. In this concept, ideally mixed homogeneous mixture is drawn in. As this method constitutes optimum mixing, this version can be regarded as a comparative base for all subsequent concepts.

The starting and peripheral conditions were derived from an existing engine concept with the aid of the one-dimensional gas exchange calculation (Figure 2.4-1). The mixture formation simulations in this and subsequent versions were based on natural gas as this is known to be very difficult to mix. This bases assumptions of the worst case. Calculations were always performed from gas exchange TDC (0° CA) up to a possible ignition timing (330° CA).

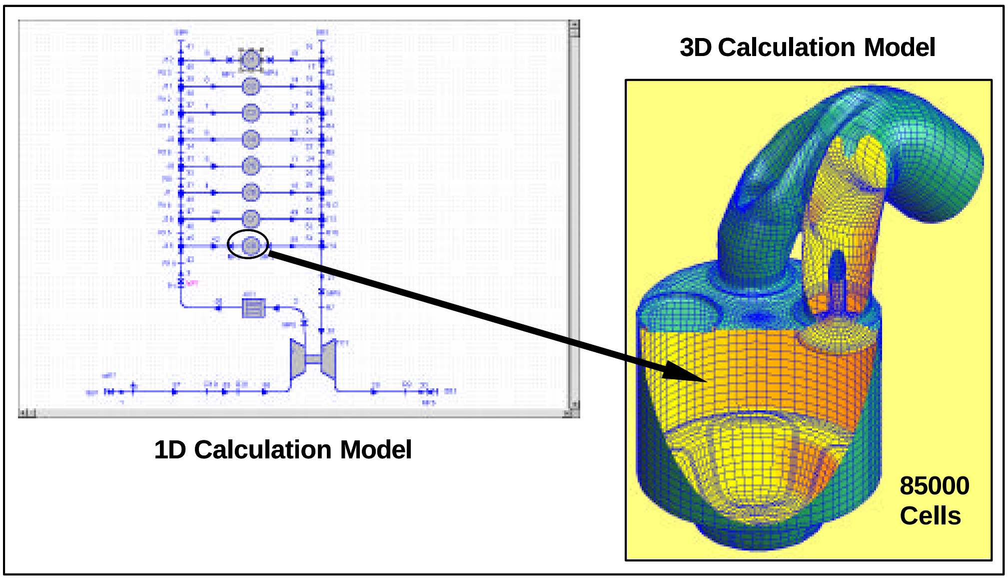


Figure 2.4-1 Start- and boundary conditions

The decisive factor for combustion is the mixture distribution at ignition timing. For the purpose of better illustration fuel distribution is only depicted at 95° CA after gas exchange TDC in 3 characteristic sections, always preserving the difference trends up to ignition timing, see Figure 2.4-2.

2.4.3 Mixture Formation Concepts

Four potentially possible mixture formation concepts were tested for suitability in a concept study:

- Gas feed via a single pipe into the intake port
- Gas feed through two pipes via the valve gap into the cylinder (Trans valve concept)
- Gas feed into a pre- (mixing) chamber
- Gas feed into the intake port near the valve gap

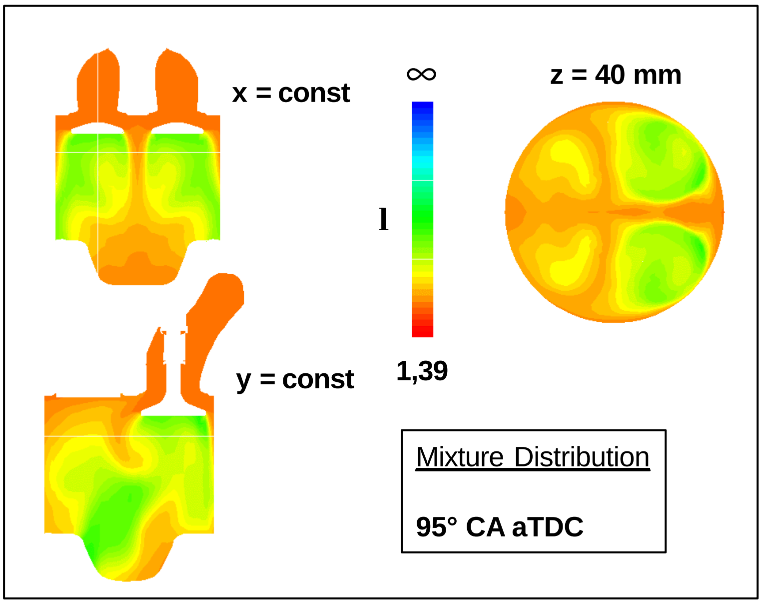


Figure 2.4-2 Mixture distribution of the basic concept

2.4.4 Selection of Concept

Comparing the four concepts presented, the last mentioned concept proved to be most promising. Jenbacher AG tested the concept with regard to possible implementation into the existing cylinder head and continued with detailed planning and manufacturing of a prototype cylinder head (see report Jenbacher AG).

2.4.5 Optimisation of the Concept

Further a 3D grid model of the prototype cylinder head was created. With the aid of CFD simulation, optimisation calculations were performed for subsequent test bed set-up. The position of the control valve and the geometric dimensions of the gas supply pipes have a decisive influence on the functioning of this concept. Moreover, it was necessary to ascertain the control times for the gas valve.

2.4.6 Mixture Formation with Pyrolysis Gas

So far, all simulations were performed with natural gas only which, as mentioned above, presents the worst case. The aim was further to demonstrate that the new concept also produced satisfactory results with regard to mixture homogeneity when using pyrolysis gas. The composition of the pyrolysis gas was taken from the *3rd periodic progress report* of the *University of Essen*. As expected, the mixture is somewhat more homogeneous than the natural gas version. The homogeneity of the mixture is adequate.

2.4.7 Test Bed Results

2.4.7.1 Adaptation of the New Cylinder Head

The cylinder head provided by Jenbacher AG was installed on the single-cylinder research engine. After an electrically controlled solenoid valve, the combustion gas enters the cylinder head via two pipes, where it is mixed with fresh air by two admission rings during the intake stroke.

2.4.7.2 Results

Figure 2.4-3 shows the efficiency of the new concept vs. nitrogen oxide content of the exhaust gas (red). The efficiency of the basic version with ideal mixing is indicated for comparison (black). As the efficiency and content of nitrogen oxide are the two most important, mutually dependent optimisation parameters, it is common practice to use this kind of trade-off diagrams. The differences between both concepts are minor.

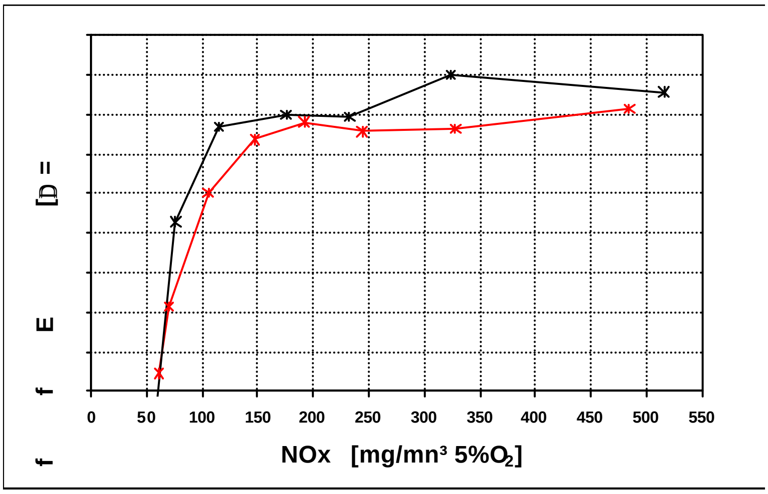


Figure 2.4-3 Efficiency vs. NO_x

2.5 Investigations on the Gasifier

In this chapter all investigations concerning the gasifier are summarised. First, the gasifier was optimised thermodynamically regarding the energy and mass flows to obtain the best operating conditions for the gasification (chapter 2.5.1). A theoretical / empirical model was made to predict the composition of the syngas (chapter 2.5.2). Due to the endothermal chemical reactions during the gasification the gasifier has to be supplied with heat. The chosen concept is presented in chapter 2.5.3. The design of the gasifier can be obtained from chapter 2.5.4.

2.5.1 Optimisation of the Gasifier by Thermodynamic Laws

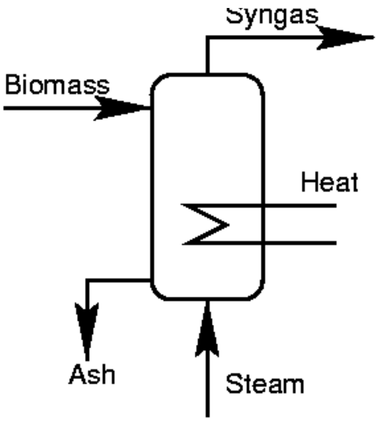


Figure 2.5-1 Model of the gasifier

A simplified model of the gasifier was made to investigate the influence of the gasification temperature and pressure as well as the influence of the mass flow of the gasification agent steam. The model is depicted in Figure 2.5-1. The steam was fed to the gasifier at gasification temperature and the biomass at ambient temperature. Thereby, it was assumed that the gas components reach an equilibrium state (chemical equilibrium). From the composition of the produced gas (see Figure 2.5-2) the lower heating value (LHV, see Figure 2.5-3) was calculated as well as the required heat that was necessary for the gasification. From Figure 2.5-3 the minimum mass flow for a complete gasification was obtained as well as the information that with increasing ratios steam / biomass the LVH decreased whereby the gasification pressure had almost no influence. The required heat for the gasification process increased with the temperature and decreased when the ratio of steam / biomass was elevated. From the thermodynamical point of view the optimal operation conditions were to keep the gasification temperature, pressure and ratio of steam / biomass as low as possible. The temperature of the steam had to be high.

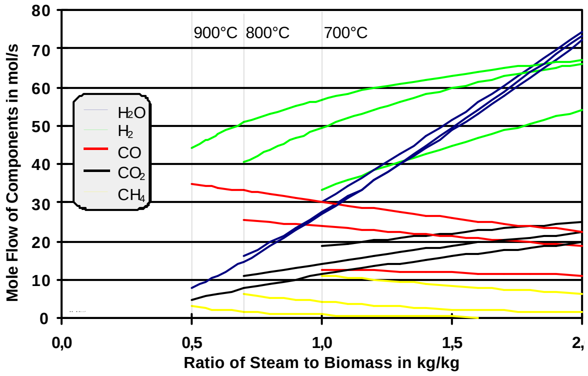


Figure 2.5-2 Mole flow of components at different temperatures and a pressure of 1 MPa against the ratio steam / biomass

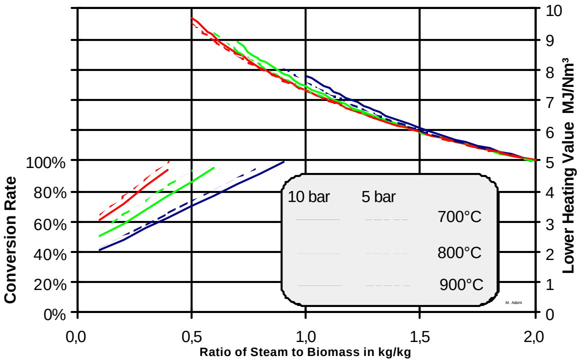


Figure 2.5-3 Lower heating value and carbon conversion rate against the ratio steam / biomass

The impact of reduced carbon conversion on the LHV was investigated as well. A reduction of the carbon conversion could occur when some of the char in the fluidised bed was entrained by the gasification / fluidisation agent or during the exchange of the bed material which had a char content of about 10%. As Figure 2.5-4 shows the LHV decreased constantly with the reduction of the conversion rate. Responsible was the lower CO content in the syngas.

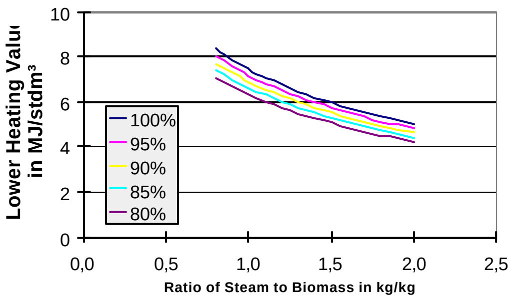


Figure 2.5-4 Influence of a reduced char conversion on the LHV at a temperature of 800°C and a pressure of 1 MPa against the ratio of steam / biomass

2.5.2 Modelling of Kinetics

A theoretical / empirical model was made to predict the composition of the syngas at steady state. It was adapted to the results gained from the gasification tests. Only chromatographable components were considered. The gasification process can be divided into three different steps: Drying, pyrolysis and char gasification (see Figure 2.5-5). As the LDU was fed from the top the drying took place in the upper region of the fluidised bed. The moisture content of the biomass was released as steam into the freeboard. During the pyrolysis solid (char) and gaseous products were formed. As small particles were applied and high gasification temperatures used a flash pyrolysis was assumed. In this case the char consisted of ash and the amount of fixed carbon given by the ultimate analysis. Gaseous products (H_2O, CO, CO_2, H_2, CH_4 and C_xH_y) were entering the freeboard as well. The last step was the gasification where the char reacted with the steam. It was assumed that this reaction achieved equilibrium state due to the high temperatures. The gaseous products (H_2O, CO, H_2) entered the freeboard alike the other gaseous components. The freeboard can be treated like a secondary reactor in which the homogenous reaction took place. These reactions were driven kinetically. From literature can be obtained that the order of magnitude of the CO-shift-reaction ($CO+H_2O \leftrightarrow CO_2 + H_2$) is several times higher than that of the other possible reactions. Therefore, only this reaction was considered. Different attempts can be found in literature to describe this reaction. Zhao [Zhao, H. et al.; Journal of Molecular Catalysis A: Chemical; Vol. 149; pp. 141 – 146; 1999] has compared these approaches so the equation of Fott [Fott, P. et al.; Collection of Czechoslowak Chemical Communication; Vol. 44; pp. 652 – 659; 1979] was taken.

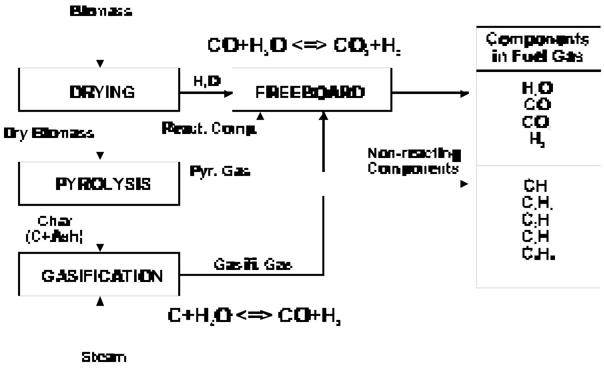


Figure 2.5-5 Model of kinetics

However, a comparison between the measured and estimated syngas composition revealed only a low accuracy. The deviation was about 10% for each component. There were three reasons for it. First, the amount of tar could not be considered that was about 10 to 20% of the fed biomass. Second, the composition of the syngas was only measured once at the end of the gasifier. A concentration profile was not available. Third, a temperature profile of the freeboard was available neither which would have been important as the kinetic was driven mainly by temperature. Alike all models for gasification in the field of biomass this model was limited to the applied biomass and bed material, the particle size as well as the used gasification conditions (temperature, pressure and gasification agent).

2.5.3 Concept for the Heat Supply

As described in chapter 2.5.1 the gasifier had to supplied with heat due to the endothermal reaction between the char (carbon) and the steam. Different concepts were investigated to achieve a suitable heat supply. On the one hand a second reactor (combustor) could be taken that was fed with a share of the bed material (including the char) from the gasifier. The char was combusted with air and the heated bed material led back to the gasifier as heat source for the gasification. The advantage of this concept was that the bed material had a high specific heat capacity. Disadvantages were that the hot bed material could led to sintering problems at the inlet of the gasifier, moreover, a large amount of hot solid material had to be transported. Therefore, another concept was taken into account where the heat was transferred to the fluidised bed via a heat exchanger. To generate the heat either syngas or char could be combusted. For the combustion of char it had to be separated from the other bed material. This procedure required a high technical effort because of the low char content in the bed material. A more suitable solution was the combustion of syngas. The temperature of the flue gas at the heat exchanger inlet was limited by the material (about 1100°C for high alloy steals). Hence, to control the inlet temperature either the combustion could be done with an air excess or cold gas could be admixed. The second option was more suitable because of a better heat integration. A concept of the heat supply is shown in Figure 2.5-6. To reduce the amount of syngas for the heat supply all streams leading to the combustor should be pre-heated as far as possible. To compensate pressure losses a compressor / blower was necessary. The outlet temperature of the heat exchanger was given by the gasification temperature and an assumed pinch of 50 K.

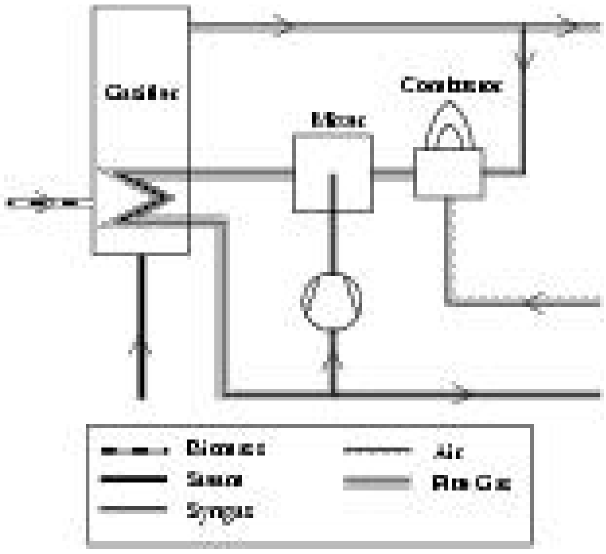


Figure 2.5-6 Concept for heat supply

2.5.4 Design of the Gasifier

Considering the work programme it was planned to design a gasifier similar to the LDU test gasifier. Therefore, the LDU was scaled-up taking into account the law of similarity principles (chapter 2.5.4.1). Unfortunately, it turned out that scale was limited to geometrical similarity. Hence, in co-operation with a technical consultant an optimised design was made. The geometry of the gasifier was fixed (chapter 2.5.4.2). To reduce the heat losses the gasifier was insulated (chapter 2.5.4.3) to enhance the efficiency. The implementation of the concept for the heat supply proposed in chapter 2.5.3 is shown in chapter 2.5.4.4. The bubble distributor is described in chapter 2.5.4.5. For a continuos operation the ash of the biomass and with it a share of the bed material has to be distracted from the fluidised bed (chapter 2.5.4.6). Finally, in chapter 2.5.4.7 the solution for the dedusting of the hot syngas is presented.

2.5.4.1 Scale-up by Law of Similarity Principles

To make best use of the results from the gasification tests the gasifier had to be scaled-up taking into account law of similarity principles considering the experience and results gained from previous tasks. The difference between the LDU and the large scale gasifier was that the LDU was designed for batch operation mode but the scaled-up gasifier should work continuously. Furthermore, the heat exchanger had to be integrated into the gasifier.

The scale-up of a system is connected with several restrictions that often not all similarity conditions can be fulfilled simultaneously. These cases are limited to partial similarity. Generally, similarity can be categorised in four classes: 1) geometrical similarity, 2) mechanical similarity, 3) thermal similarity and 4) chemical similarity. A geometrical similarity is given if all each other corresponding longitudinal dimensions are in a same relation to each other. The quotient of the longitudinal dimensions must be alike for all three space dimensions. The mechanical similarity characterises the static, kinematic and the dynamic behaviour of two systems. It is fulfilled if in a geometrically similar system the particles move in corresponding time geometrically similarly. The velocities (amount and direction) of the particles have to be in a constant relation to each other at corresponding places. A thermal similarity is present, if geometrical and kinematic similarity is given and the temperature differences at corresponding places have a constant relation. Two similar systems are indicated by similar temperature profiles. A chemical similarity is given if the three previous similarity conditions are fulfilled and appropriate concentration profiles have a constant relation.

Generally, there are infinite solutions for the geometrically scaled-up gasifier, however, it should be as small as possible regarding economy. The diameter of the bed has to be large enough for the integration of the heat exchanger but should be small to reduce the amount of steam necessary for fluidisation. The higher the steam mass flow was the lower was the LHV of the syngas (see chapter 2.5.1). One suitable solution for a gasification system with a power output (the lower heating value multiplied with the mass flow of the syngas) of 2.5 MW was a bed diameter of 1.5 m for the scaled gasifier. In Table 2.5-1 the longitudinal dimensions for the LDU and for the scaled gasifier shown in Figure 2.5-7 are given. The shape of the LDU reactor had to be changed a little due to the integration of the heat exchanger. The distributor applied in the LDU was funnel shaped and had a volume of about 0.001 m^3 (or 1 dm^3). This was half of the volume of the bed material in the LDU (0.002 m^3). The heat exchanger should be distributed over the whole height of the bed to achieve a reasonable heat transfer and to prevent the cooling down of the lower part of the bed. A design of a heat exchanger which followed the shape of the distributor would be connected with high effort in regard to construction. The application of a cylindrical shape of the fluidised bed solved this problem.

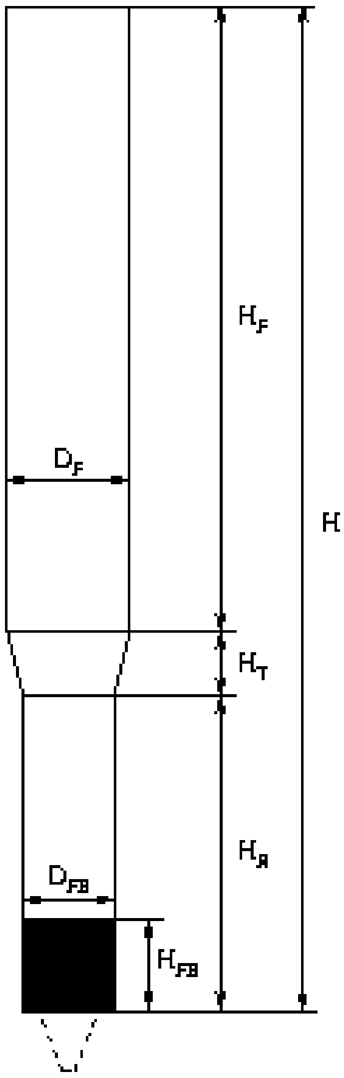


Figure 2.5-7 Sketch of the gasifier

Table 2.5-1 Data for geometrical scale

Longitudinal Dimension	Dimension in Fig. 1	Unit	LDU	Scaled Gasifier
Diameter of Fluidised Bed	D_{FB}	m	0.144	1.500
Height of Fluidised Bed (in operation)	H_{FB}	m	0.147	1.536
Ratio of Height to Diameter		-	1.023	1.024
Scale Factor		**-**	**10.425**	
Height of Reaction Chamber	H_R	m	0.510	5.317
Height of Transition	H_T	m	0.104	1.084
Diameter of Freeboard	D_F	m	0.200	2.085
Height of Freeboard	H_F	m	1.010	10.529
Height overall	H	m	1.624	16.929

Fizgerald & Crane (T.J. Fitzgerald and S.D. Crane, Proc. 6th Int. Conf. on Fluidized Bed Combustion, vol. 3, p. 815, Atlanta, GA, 1980; T.J.Fitzgerald, Fluidization, J.F. Davidson et al., eds.,p. 413, Academic Press, New York, 1985) propose the set of conditions shown in Table 2.5-2 to predict similarity of hydrodynamic behaviour (mechanical similarity) in different fluidised beds. L represented the height of the bed. Starting with the forth constraint, the particle size d_P was fixed as the lengths of the reactors were known as well as the particle size used in the LDU reactor. The velocity u of the steam in the LDU was known, so from the third condition the velocity of steam in the scaled gasifier could be estimated (gravity of earth, $g = 9.81\ m/s^2$). The ratio of density ($\rho_{Solid} / \rho_{Gas}$) was identical as the same bed material and same operating conditions were applied in both reactors. To fit the first condition for similar hydrodynamic behaviour the dynamic viscosity η of the steam had to be adapted. All other parameters were given by constraints two to four. But the viscosity was fixed through the operating condition (temperature and pressure) and therefore no free parameter. Hence, it was not possible to achieve similar hydrodynamic conditions in the scaled-up gasifier. Because of this it was not possible to achieve thermal and chemical similarity, neither.

Table 2.5-2 Conditions for mechanical similarity

1. Reynolds number $\frac{d_P u \mathbf{r}_g}{\mathbf{h}}$	2. Density ratio $\frac{\mathbf{r}_S}{\mathbf{r}_g}$
3. Froude number $\frac{u}{\sqrt{g \cdot d_p}}$	4. Geometric similarity of distributor, bed and particle $\frac{L}{d_P}$

2.5.4.2 Geometrical Size

As described in the previous chapter the scale-up of the LDU was limited to geometrical similarity. Because the constraint for mechanical similarity was not fulfilled the gasifier had to be re-calculated to ensure stable operation conditions. Thereby, the geometry was optimised considering published experiences from industry gained in the field of fluidisation technology over the past years.

The ratio of height to diameter of the LDU was about 1. In large scale applications often ratios up to 3 – 4 are chosen. With this change the contact time between the biomass char and the steam and consequently the conversion ratio increased which would lead to less steam excess and therefore improve the efficiency. Another advantage was that the operational characteristic of the heat exchanger improved. The minimum inner diameter for the integration of the heat exchanger was 1.15 m that resulted in a height of the fluidised bed of 2.86 m. The ratio of height to diameter was about 2.5.

The freeboard has two different objectives. On the one hand it is a secondary chemical reactor in which gaseous reactions take place. On the other hand the amount of entrained particles could be influenced by the height. The last objective is the guiding parameter for the lay out of fluidised beds in industry. The entrainment of particles is caused by the superposition of two phenomena: 1) The particle size decreases by a constant abrasion caused by the strong solid movement inside the fluidised bed through the bubbles. If the particle size is small enough the drag force of the upward moving gas becomes higher than the weight force and the particle is entrained. 2) Some of the particles are ejected into the freeboard by the eruption of the bubbles at the surface of the bed. Closely above the surface the particle density in the gas is very high. With increasing height the influence of the bubble eruption decreases. The height between the point where the influence of the bubble eruption becomes neglectable and the surface of the fluidised bed is defined as transport disengaging height (TDH). The height of the freeboard should be above the TDH. It was estimated by semi-empirical equations to about 2 m. To ensure this an overall height of 6 m for the reactor was chosen that resulted in a height of the freeboard of 3.14 m. Compared to the height estimated from the geometrical scale it was much lower. The geometrical size of the reactor is shown in Table 2.5-4.

Table 2.5-4 Geometrical size of the gasifier

Dimension	Size
Inner diameter	1.15 m
Height of the fluidised bed	2.86 m
Height of the freeboard	3.14 m
Height overall	6.0 m

materials taken into account are listed in Table 2.5-3.

Technical name (German)	Name	Density kg/dm^3	Porosity %	Reversible elongation at 1000°C	Thermal conductivity W/(m*K)	
					At 400°C	At 800°C
OFL 54	Chamotte Brick	0.55	80	0.5	0.16	0.21
OFL116	Corundum	1.1	60	0.5	0.34	0.82
OFL117	Corundum	1.1	70	0.75	0.80	0.71
OFL138	Corundum	1.35	65	0.8	0.97	0.97
FL 42	Corundum	1.2	- -	0.98	0.68	0.57
ISO 18 L	Corundum	1.3	- -	- -	0.71	0.80
IK 50 M	Hard chamotte (multi-base)	2.35	18	0.5	1.62	1.62

Table 2.5-3 Physical properties of the insulation material

The best option is depicted in Table 2.5-5 beginning from the inside. The lightweight refractory bricks OLF 138 and OLF 54 had good insulating properties and can withstand high temperatures. The V2A steel was used as barrier to prevented the penetration of steam into the colder areas of the insulation and the subsequent condensation. The ZrO_2 fibre mat as well as the Al_2O_3 fibre mat was used to compensate thermal expansions. The asbestos was used for compensation of thermal expansions as well and for the protection of the metallic

Material	Thickness mm	Share of material on insulation effect
OLF 138	125	9%
OLF 54	125	39%
ZrO_2 Fibre Mat	5	2%
V2A Steel	7	0%
AL_2O_3 Fibre Mat	7	5%
OLF54	125	40%
Asbestos	5	1%
Reactor Wall	3	0%

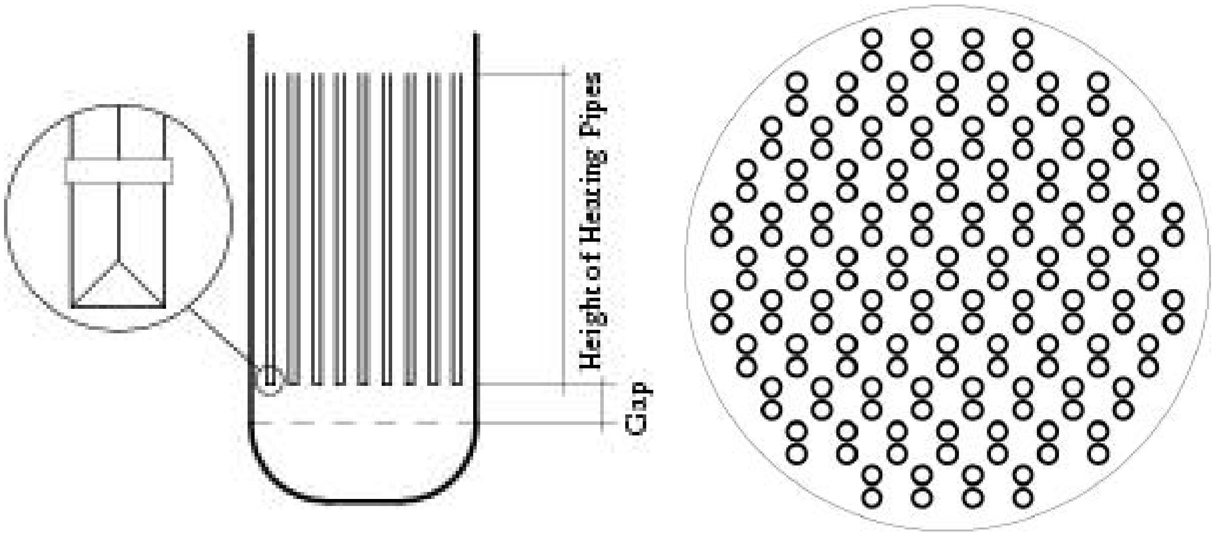
Table 2.5-5 Gasifier insulation

reactor wall. Between metal and brick always a fibrous material was necessary due to the different thermal elongation. As reactor wall a stainless steal for low temperature application was taken.

2.5.4.4 Heat Exchanger

As discussed in chapter 2.5.3 a heat exchanger was used to supply the gasifier with heat. The diameter of the gasifier was given by the size of the heat exchanger. To achieve a dense distribution of the heating pipes a triangular arrangement was chosen. To reduce the material stress by the fluidisation a hairpin shape for the pipes was selected. The Figure 2.5-8 a shows how the heating pipes were immersed into the fluidised bed. Between the distributor of the fluidised bed and the heating pipes a space (gap) was necessary because in the lower region of the bed the solid movement in the bed was high and therefore the erosive impact. Moreover, the feeding of the biomass was done in this area. Each hairpin pipe was taped with a metal strap to fix the pipes against each other. The strap was fixed at only one pipe to prevent wrapping through thermal elongation. The arrangement of the hairpin pipes of the applied heat exchanger is depicted in Figure 2.5-8 b. More information are given in Table 2.5-6.

The large wall thickness was chosen to prevent the destruction of the heat exchanger through the erosive impact of the fluidised bed. The hot flue gas had a pressure of about 5 bar which was 1 bar higher than the gasification pressure. Although the pressure had no influence on the heat transfer an elevated pressure was chosen for three reasons: 1) The high pressure reduced the volume flow of the flue gas and the velocity – which was a critical point – inside the tubes. A smaller heat exchanger with less tubes could be chosen. As the used material was expensive this would reduce the costs. 2) The pressure losses inside the tubes depend strongly on the velocity of the gas as well ($\Delta p \sim v^2$). The pressure losses inside the heat exchanger were reduced dramatically down to 0.024 bar. Hence, the power consumption of the compressor for the cold flue gas (see Figure 2.5-6) was reduced. 3)



a) Sketch of the heat exchanger in the fluidised bed (front view)

b) Arrangement of the heat pipes of the heat exchanger (top view)

Figure 2.5-8 Integration of the heat exchanger

Another advantage regarding safety aspects was that in case of a broken pipe no bed material could invade into the heat pipes leading to further damage.

Table 2.5-6 Heat exchanger specifications

Item	Size
Number of pipes	85
Height of pipes	2.2 m
Outer diameter of pipes	50 mm
Wall thickness of pipes	10 mm
Pitch	110 mm

2.5.4.5 The Bubble Distributor

The objective of the distributor was the generation of bubbles at the bottom of the fluidised bed. The bottom of the gasifier was funnel shaped. The steam entered through a pipe the steam collector below the bottom (see Figure 2.5-9). On the bottom distributor pipes were install which were fed with the steam coming from the collector. The arrangement of the distributor pipes is shown in Figure 2.5-10. The bores were pointing downwards distributed uniformly over the length (see Figure 2.5-11).

The steam collector was double-walled to prevent the penetration of super-heated steam to the reactor wall and its thermal destruction in case of an accident. Furthermore, the steam

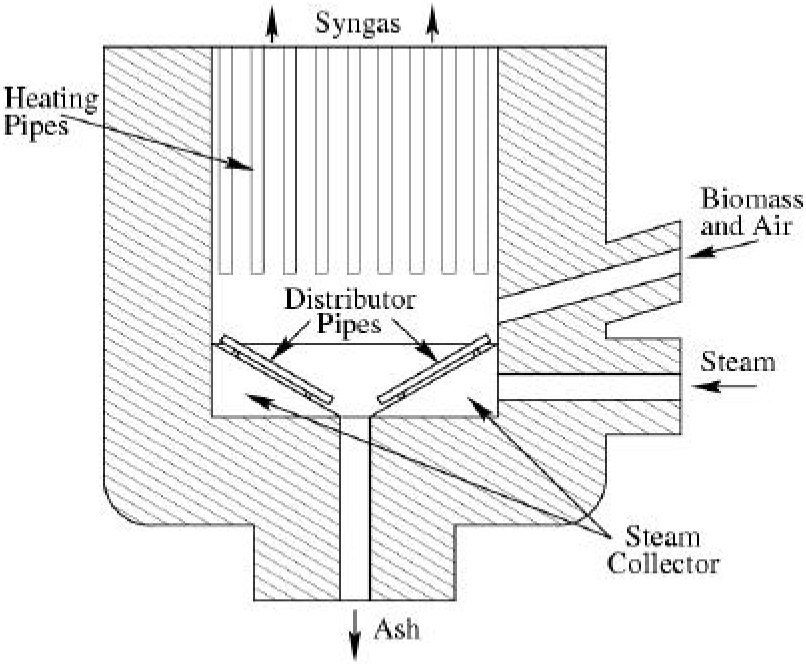


Figure 2.5-9 Arrangement of the distributor in the gasifier

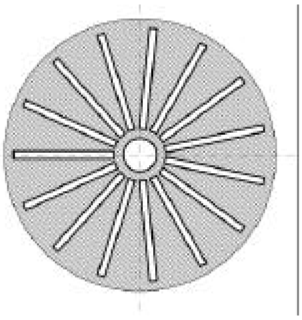


Figure 2.5-10 Arrangement of distributor pipes

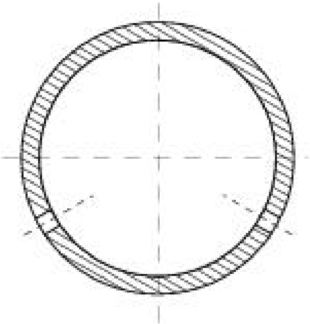


Figure 2.5-11 Cross cut of distributor pipe

pipe had to be insulated against the reactor wall for the same reason.

2.5.4.6 Distraction of Ash

The distraction of the ash was done through the bore in the middle of the bottom (see Figure 2.5-9). To achieve a suitable ash distraction the bottom was funnel shaped. The ash fell into a cooled pipe that ended at a cell wheel sluice. The ash was accumulated there alike a fixed bed. With the sluice a continuous distraction was feasible wherewith the level of the fluidised bed was controlled. From the sluice the ash fell into one of two repositories that were filled discontinuously. As one repository was filled the other was emptied and the ash was conveyed pneumatically. The usage of the repositories was necessary to hold the pressure inside the gasifier because the cell wheel sluice was not pressure proof. It had to be taken into account that not only ash alone was distracted but also bed material.

2.5.4.7 Hot Gas Dedusting

As described in chapter 2.5.4.2 the amount of entrained particles depended on the height of the freeboard. However, even at a height above the TDH still some small particles are entrained. To prevent their harmful impact on subsequent components like e.g. heat exchangers they have to be separated from the hot syngas. Alike the pipe for steam feeding (see chapter 2.5.4.5) the pipe for the hot syngas had to be insulated. For the dedusting at this temperature a cyclone was the best solution. The solids were fed back into the feeding pipe by cell wheel sluice similar to the system taken for the ash distraction (see chapter 2.5.4.6) whereby repositories were not necessary because of the low pressure difference.

2.6 Biomass Feeding Tests

The suitability of a feeding system depends mainly on the used feed. The particle size, particle shape and in particular agglomeration tendencies are of interest. Disturbances during the feeding process can occur for two reasons: 1) If the temperature of the biomass exceeds a value of above 200°C first pyrolysis products can be formed, the biomass particles can soften and agglomerate 2) The particles can drop out of the conveying stream and constipate the feeding pipe. Published articles concerning feeding experiences showed that both problems were solved if the biomass was fed into the lower zone of the fluidised bed by a jet stream. The operational principle of feeding by a jet stream is shown in Figure 2.6-1. The biomass entered the fluidised bed together with the transporting agent (air). To achieve a good mixing of the feed within the fluidised bed an additional stream (steam) was blown in concentrically. The pneumatic feeding was less accident sensitive if the whole feeding pipe was leading downwards and turnarounds of the pipe were done applying slight curves only (Figure 2.6-2).

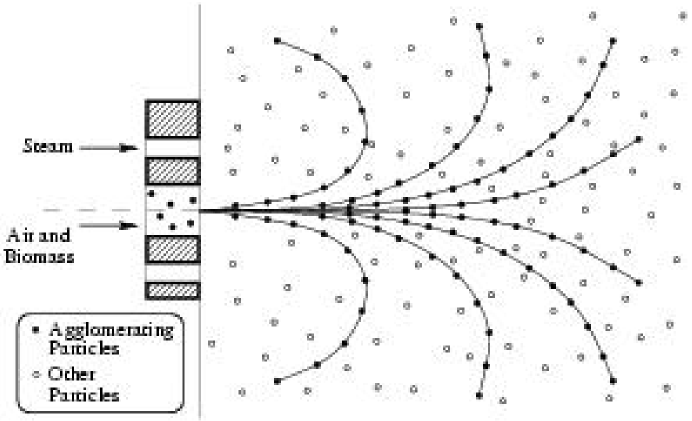


Figure 2.6-1 Mixing of particles fed with a jet stream

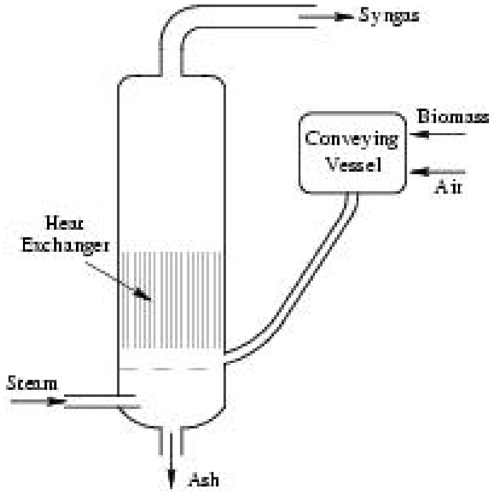


Figure 2.6-2 Arrangement of feeder and gasifier

a) Conveying under pressure

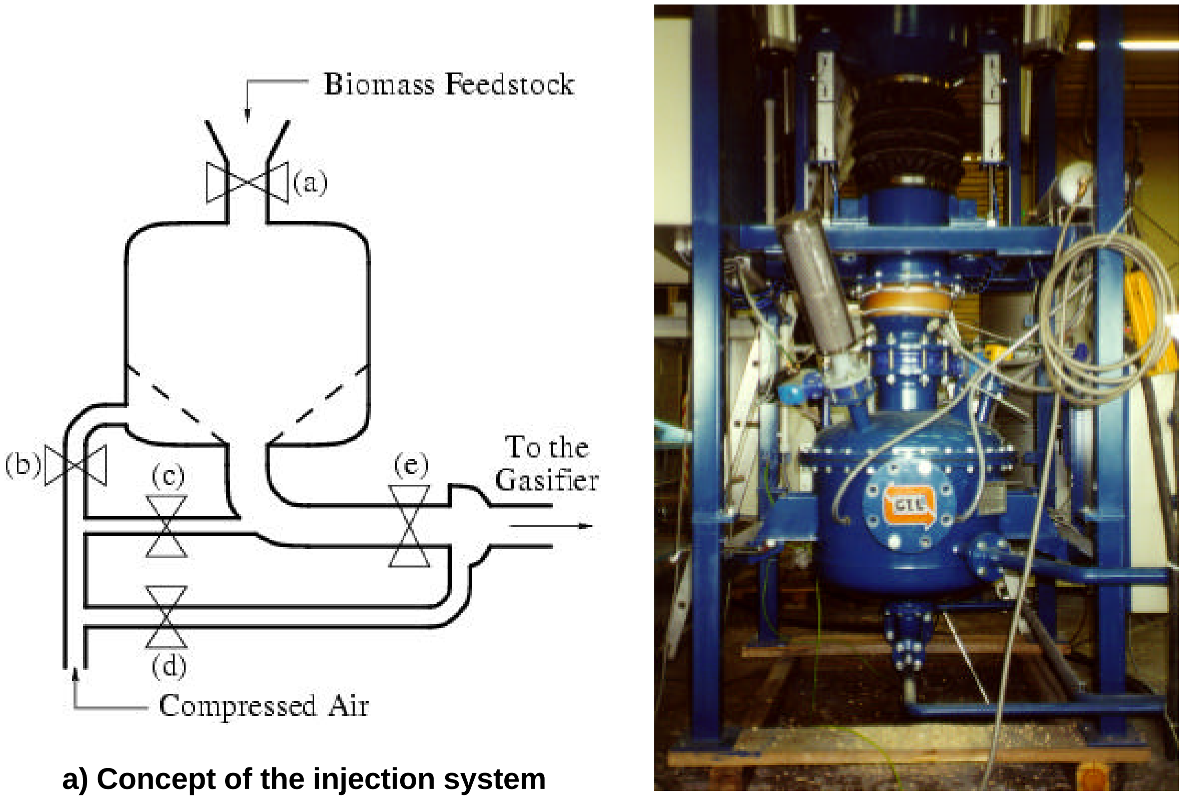
b) Conveying by an injection system

Figure 2.6-3 Conveying concepts

2.6.1 Feeding Facility

Generally, two different concepts of conveying are feasible (see Figure 2.6-3): a) Conveying under pressure b) Conveying by an injection system. The difference between the concepts is that with the injection system the transporting agent and the solid material is fed into the feeding pipe simultaneously. Air was chosen as transporting agent. As the gasification was done by steam the amount of air in the gasifier should be low. The conveying density of the injection system was higher therefore it was selected.

The tested injection feeding system is shown in Figure 2.6-4. At the beginning of a feeding cycle only valve (a) was open. From the top the feed dropped down into the conveying vessel until a level gauge signalled to close the valve (a). The pressure charging was done through valve (b) whilst the other valves were closed. With the valves (b), (c) and (d) the conveying process was controlled. Valve (b) controlled the amount of air for the fluidisation of the feed. With valve (c) air for the conveying was added. The task of valve (d) was to add auxiliary air for the transport if required. Feedstock with good conveying properties could be transported using only air for fluidisation. With this setting the highest conveying density could be achieved. After the pressure charging the valves (c), (d) and (e) opened as well and the biomass was conveyed. When the vessel was emptied all valves closed, the pressure in the vessel was balanced with the ambit and valve (a) opened for another conveying cycle.



a) Concept of the injection system

b) Picture of the tested feeder

Figure 2.6-4 The feeding system

2.6.2 Used Biomass

Two different biomass fuels were selected for the feeding tests. The first one had a cylindrical shape (pellets) and the second one was wood splinters from wood processing industry. Both are shown in Figure 2.6-5 as well as a mixture of both. The size distribution of the wood splinter is shown in Table 2.6-1. The moisture content of the splinters was very high (about 70%wt). With drying the moisture content was reduced down to 5%wt under ambient conditions after a week. The pellets had a diameter of 6 mm and an average length of 13 mm. Their moisture content was about 9%wt.

Table 2.6-1 Particle size distribution of the wood splinters

Particle size mm	Particle size mm	Share %wt
	> 5.000	11
5.000	2.500	24
2.500	1.000	45
1.000	0.630	18
0.630	0.000	2

a) Pellets

c) Mix of wood splinters / pellets (wt: 20% / 80%, vol: 50% / 50%)

b) Wood splinters

Figure 2.6-5 Used biomass

2.6.3 Results from the Tests

At the above described conveyor several measures were investigated to optimise the transport of the biomass. The distribution of the air mass flow into air for fluidisation, air for conveying and secondary air for conveying could be varied. With the air for fluidisation the amount of fed material could be controlled within a certain range. The start pressure in the conveyor vessel was only of minor interest. With it the first pulse of feed into the pipe was controlled. To obtain a steady-ongoing transport without pulsing of feed in the pipe the start pressure had to be closely above the feeding pressure. The minimum pressure in the feeding pipe controlled the stop of conveying. The lowest value could be the pressure losses of the feeding pipe without transport of material. It was connected with a pre-adjusted timeout of about 10 seconds for which the pressure had to be below that value to prevent undesired stops if pulsing in the pipe occurred. The feeding tests had to show whether the selected biomasses could be transported without disturbances. As the gasification was done with steam the amount of required air for the transport should be low. Hence, the ratio of transported mass per kg air was of particular interest.

2.6.3.1 Pellets

The tests with the pellets were performed without any disturbances. Only the air for fluidisation was necessary (only valve (b) was opened in Figure 2.6-4a). A high conveying density (load) of about 23 kg_{Feed} / kg_{Air} in average was achieved. The start pressure in the conveying vessel had only a minor influence. A reduction of the feeding pipe diameter did not lead to significant changes in the load but led to a more even conveying. With a pipe diameter of 90 mm the pressure inside the pipe changed about ±0.2 bar. Using a smaller pipe the pressure was almost constant at a value of about 0.3 bar. After a conveying cycle no pellets were left in the conveying vessel. Tests runs with a pipe diameter of 50 mm failed as the transition from 90 mm which was the outlet diameter of the conveying system and could not be changed to the 50 mm pipe was blocked. The results of the test series with pellets are summarised in Table 2.6-2.

Table 2.6-2 Results from the feeding tests series with pellets

	Test series 1	Test series 2	Test series 3
Diameter of the feeding pipe in mm	90	90	70
Start pressure in the conveying vessel in bar (above p_u)	1.0	0.4	0.4
Average load in kg_{Feed} / kg_{Air}	24.5	22.8	22.9
Average conveying time in s	31	35	35
Average mass transported in kg	70	73	71.5

2.6.3.2 Wood Splinters

The tests runs with the wood splinters turned out to be more difficult. All tests to feed the wood splinters alone failed. Responsible for it was an enormous bridge-building tendency. It was impossible to fluidise the feed laying on the funnel. The feed was lifted and hovered on the distributor. The air provided for fluidisation disappeared through the outlet. To thwart this effect four nozzles uniformly distributed around the perimeter were installed through which compressed air impulses were injected. However, even this measure was unsuccessfully as only wholes were shot into the filling but wood splinters were not intermixed. Probably, nozzles implemented in the air distributor through which highly compressed air pulsed could solve this problem. They would have to be arranged that a compaction of the wood splinter filling is excluded in any case. Unfortunately, it was impossible to test this solution because it would have exceeded the foreseen budget several times as in principle a new feeding system had to be build.

Another solution to counteract the bridge-building tendency was the admixing of other material to improve the conveying characteristics. As the pellets showed very good conveying properties a mixture of both was tested. The first mixture consisted of 10%wt splinters and 90%wt pellets what represented a volumetric proportion of 24% splinter and 76% pellets. Pre-tests with this mixture showed that all three air mass flows for fluidisation and transport had to be carefully adjusted to each other. As some of the feed remained at the wall of the conveying vessel the above mentioned four nozzles were used to blow it off. The nozzles were driven in two different modes. The first was to activate them in rotation, the second was to activate two opposite nozzles simultaneously. The second option was taken into account as the number of impulses was doubled and therefore a quicker cleaning was expected. However, the results were worse than achieved with the rotation mode. The reason was that in rotation mode the blown particles reached the other side of the vessel where they carried off the particles sticking at the wall. This effect was not achieved in the opposite mode as the particles hit each other in the middle of the vessel and dropped down.

As mentioned above the command signal for the feeder to stop the feeding operation was the pressure inside the feeding pipe. When a high value was chosen short cycle times with a high load were obtained. The disadvantage was that a lot of feed remained in the vessel and that the conveying was uneven. A smooth operation was achieved when a lower pressure for the command signal was taken whereby the cycle time extended. The results from the test series are shown in Table 2.6-3. At all tests the start pressure was set to 0.1 bar and a pipe diameter of 90 mm was taken. The best pressure was 0.1 bar at which the amount of remain was acceptable and the load was sufficient.

Table 2.6-3 Results from the feeding test with wood splinters I

Test series	Stop pressure p_{Stop} in bar (above p_u)	Average mass transported in kg	Average time in s	Average load in kg_{Feed} / kg_{Air}
No. 1	0.07	48.3	57.0	9.44
No. 2	0.08	50.5	49.5	11.37
No. 3	0.09	40.0	43.5	10.02
No. 4	0.10	40.3	34.7	12.94
No. 5	0.11	29.7	21.5	15.43
No. 6	0.12	28.0	21.5	14.53
No. 7	0.13	26.5	19.0	15.48

Having found suitable conditions for the feeding of the mixture of splinters and pellets the share of splinters was increased to find out up to which value a feeding was feasible. The results are summarised in Table 2.6-4. At a share of 25%wt wood splinters a feeding was hardly feasible and accompanied by several constipation. As to be seen from Table 2.6-4 less material was transported in a longer time and the load decreased. Responsible for it was the lowering bulk density. For these test series the stop pressure was set to 0.1 bar and a pipe diameter of 90 mm was taken.

Table 2.6-4 Results from the feeding test with wood splinters II

Test series	Share of splinters in %wt	Average mass transported in kg	Average time in s	Average load in kg_{Feed} / kg_{Air}
No. 1	10	40.3	34.7	12.94
No. 2	15	48.5	48.7	11.12
No. 3	20	38.7	40.0	10.78
No. 4	25	27.0	27.0	11.02

2.6.4 Conclusions

The feeding tests showed that the feeding of pellets was no problem. They had good conveying properties and a high load was achieved. In contrast the feeding of the wood splinters caused problems and a feeding was only feasible when pellets were admixed. The maximum share of the splinters on the mixture was 20%wt which was equivalent to about 50%vol. Due to the lower bulk density the load was lower. The drying of the biomass was very important. If with drying under ambient conditions a reduction of the moisture content is not possible it is urgently necessary to implement a drying facility to a biomass processing plant.

Moreover, the conveying properties depended on the position of the feeder and the destination (gasifier) to each other which could not be investigated. In the tests the feed had always to be conveyed upwards that would be the worst arrangement. Furthermore, the diameter as well as the properties of the feeding pipe had influences.

Considering the above mentioned aspects the tested injector feeding system was the best solution for a pressurised feeding. The feeding characteristics of the wood splinter were much better if a suction system was used which was shortly tested but not suitable for a pressurised feeding.

Further experiences during the tests had shown that it was very doubtful whether a screw feeder or a cell wheel feeder could be used for the wood splinters due to their fibrous nature. Tests with a screw feeder failed after a very short while as the screw was blocked.

The feeding test were performed under ambient conditions. To estimate the required air mass flow for conveying the same particles at a different temperature or pressure the Reynolds number of the particle had to be constant. If the same pipe diameter was used the ratio of the air mass flows was equal to the ratio of the dynamic viscosity. As the dynamic viscosity depended only on the temperature but not the pressure Figure 2.6-6 can be taken to estimate the required mass flow.

The injection feeder can operate continuously. Therefore, a facility for continuos dosing of feed into the vessel is necessary. Principally, this could be done with a cell wheel feeder if the pressure inside the vessel was not too high. This would be suitable for the pellets but not

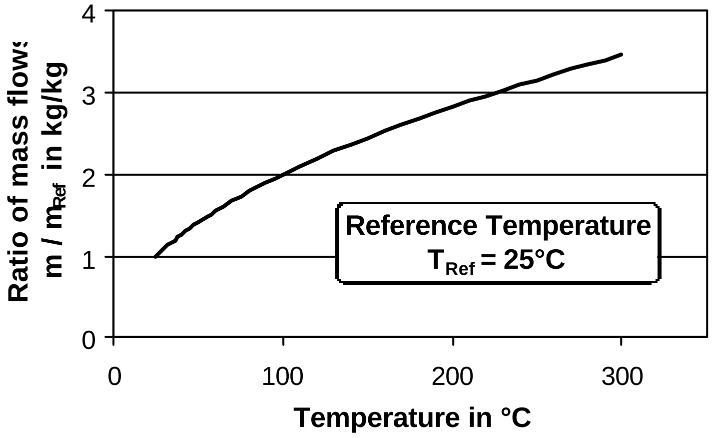


Figure 2.6-6 Required air mass flow for feeding at different temperatures

for the splinters. Another solution would be to take a smaller injection feeder as dosing unit. The time for charging of the smaller feeder should not influence significantly the feeding characteristics of the larger feeder. For a semi-continuous operation two injection feeder could be taken that feed the gasifier alternately.

2.7 Design of the Gasification Unit

In this chapter the development of the concept for the gasification unit is described. The boundary condition for the gasification were fixed taking into account the results from the theoretical optimisation as well as the gasification tests. A concept for the heat integration and the gas treatment was made. The gasification unit was thermodynamically optimised and thereafter simplified due to economy. The heat exchangers applied in the heat recovery process were engineered.

2.7.1 Operating Conditions of the Gasifier

First, the operation conditions of the gasifier had to be fixed. The thermodynamical optimisation of the gasifier (chapter 2.5.1) showed that the gasification temperature should be as low as possible. On the other hand the gasification tests demonstrated that temperatures higher 800°C were necessary to achieve a suitable char gasification. Therefore, the gasification temperature was set to 850°C. The gasification pressure depended on the required inlet pressure of the syngas at the gas engine. The inlet pressure should be about 3 bar. Hence, a gasification pressure of 3.7 bar was chosen as pressure losses for cooling and dedusting had to be considered. There were two constrains regarding the steam mass flow for the gasifier: 1) The mass flow had to be high enough to ensure a complete carbon conversion and 2) it had to be high enough to fluidise the bed material but low enough to avoid the prompt entrainment of the particles. With a steam mass flow of 80% of the fed biomass and the described geometry of the gasifier (chapter 0) both constrains were fulfilled and the heat exchanger could be integrated without problems. As the gasification tests showed the tar content was reduced significantly if air was admixed. For this reason it was chosen to feed the biomass with air into the gasifier. The allowable temperature of the biomass during the feeding was in range of 180 to 200°C. Above this value first pyrolysis steps occurred and liquid products could lead to agglomeration of the particles. Taking into account the results from the feeding tests the amount of air was a third of the fed biomass. The objectives of the heat exchanger in the gasifier were the heat supply of the gasification process and the compensation of the heat losses through the wall of the gasifier as well as losses caused by distraction of ash / bed material. To have a firm base the required heat for the above mentioned matter a factor of safety of 1.3 was chosen. The pressure inside the heating pipes was set to 5 bar.

2.7.2 Heat Integration

To achieve a good efficiency of the biomass gasification unit a well tuned heat integration was necessary. Heat sources in the process were the produced syngas, the flue gas from the heat supply of the gasifier and the exhaust gas from the gas engine. Streams to be heated were the steam for the gasification as well as the syngas and the air for the combustion for the heat supply of the gasifier. With heat that could not be recovered for the process district heat was generated.

2.7.3 Gas Treatment

To meet the gas engines requirements the raw syngas from the gasifier had to be treated. The gas was dedusted twice. The first dedusting at high temperatures directly after the gasifier by a cyclone was necessary to led entrained particles back to the gasifier and to protect the subsequent components from erosion or plugging. Because the separation properties of cyclones were not good enough for the gas engine requirements a fibrous filter as second dedusting device was necessary. The application of a fibrous filter was limited by the temperature and therefore done in a later stage of the gas treatment.

A problematic matter revealed by the gasification tests was the amount of tar in the syngas. It could not be reduced significantly by changing the operating conditions or bed material and was much too high for direct combustion in gas engine as originally planned. Therefore, a literature survey was done to find an appropriate tar treatment. Results of the survey were: 1) The tar treatment of biomass derived gases is very difficult and up to date not state-of-the-art. 2) A catalytic tar cracking device would be most suitable for this biomass gasification unit. 3) If a catalytic device is applied the amount of ammonia would be reduced simultaneously. For the catalytic reactions high temperatures are necessary and therefore the device was situated directly behind the hot gas dedusting.

The engineering of a catalytic reactor was not part of this project. Other EU-funded projects are dealing presently with that subject and their results should be implemented when they are finished. For the calculations the tarry educts were converted to CO CO_2 and H_2 whereby the mol flow of all elements (C, O and H) were balanced.

2.7.4 Thermodynamically Optimised Concept

The thermodynamically optimised concept is shown in Figure 2.7-1. Compressed air and the biomass feedstock were fed via the injection feeder into the gasifier. The steam for the gasification entered the gasifier at the bottom. The syngas was dedusted by a cyclone wherefrom the solids were recycled to the gasifier. After the catalytic cracking the syngas was cooled down in several steps whereby steam was super-heated, air and the syngas for combusted were heated and district heat produced. After a fine dedusting to meet the gas engine requirements the syngas was further cooled down to the gas engine inlet temperature of 70°C and pressure of 3 bar. A small share of the syngas was compressed to 5 bar, re-heated (840°C) and fed to the combustor where it was combusted with compressed and heated air (850, 5 bar). Recycled cold flue gas (900°C) was admixed to achieve the desired inlet temperature for the heat exchanger of 1100°C. Leaving the gasifier and after the split the flue gas was throttled and used for heating and district heat generation. The exhaust gas from the gas engine was integrated into the heat recovery process as well.

With the thermodynamically optimised process the steam, the air and the syngas for combustion could be heated close to the gasification temperature. A complex heat integration was necessary and a lot of heat exchangers were required, some of them operating at high temperatures.

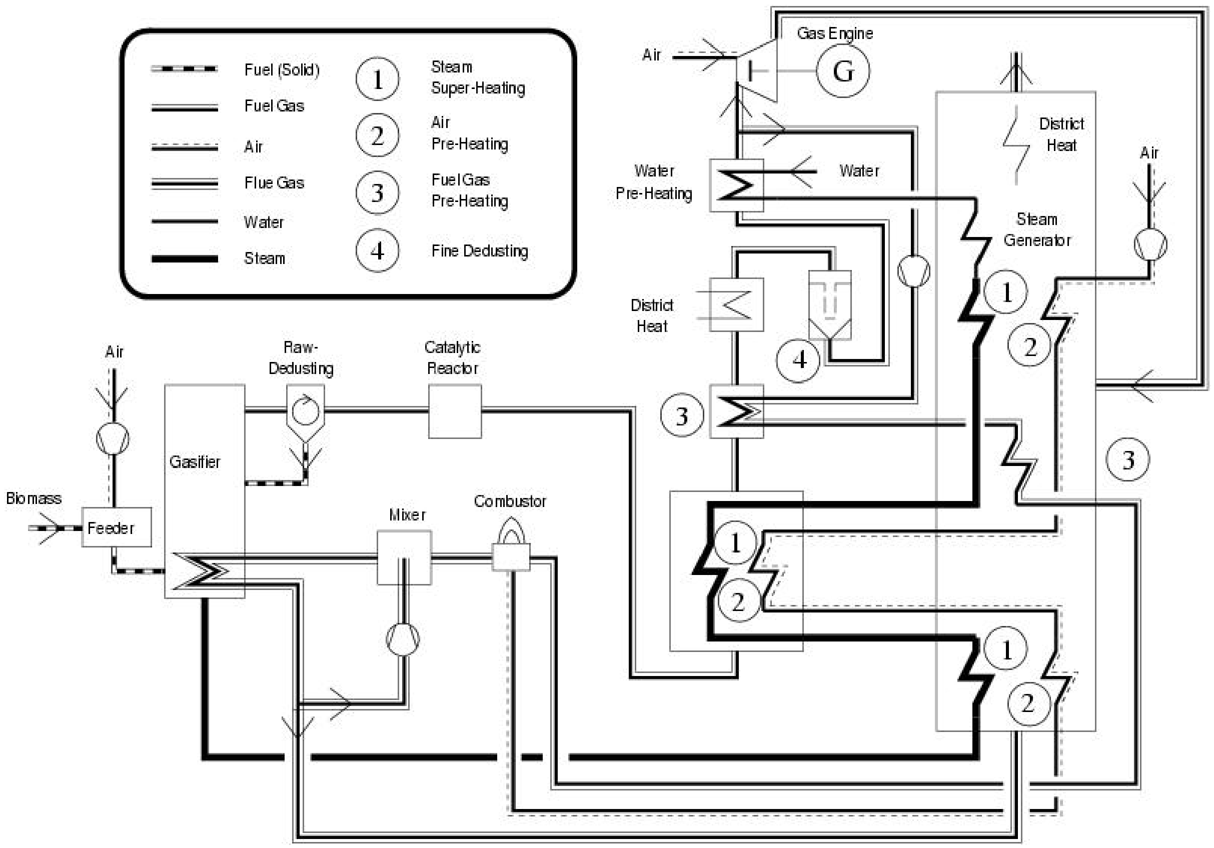


Figure 2.7-1 Thermodynamically optimised concept

2.7.5 Economically Optimised Concept

One of the objectives of the project was the simplification of the gasification unit to reduce the investment costs. As to be seen from Figure 2.7-1 a lot of heat exchanger equipment was needed to heat the streams. Shell and tube heat exchanger were taken. The price of such devices depended linearly on the heat exchanger surface and exponentially on the temperature of heat transfer. Therefore, the influence of less heated streams on the overall efficiency was investigated. Setting the efficiency at stream temperatures of 850°C to 100% the reduction of the efficiency can be seen for lower temperatures of fuel gas (syngas), air and steam in Figure 2.7-2. Additionally, the influence of a simultaneous temperature reduction (all streams) is depicted. Due to the low mass flow the influence of a lower temperature of the syngas for the combustor on the efficiency was small. The impact of the combustion air and steam temperature was similar whereby temperature reduction of steam was limited as it had to remain in vapour phase. At a simultaneous temperature reduction down to 500°C still 87% of the former efficiency was available. It was chosen to operate at this temperature because materials for construction were well known and used in power plants.

The economically optimised concept is shown in Figure 2.5-1. The following changes were done: Before entering the heat recovery process the syngas was quenched with recycled syngas that was taken from the syngas cooling path at the lowest temperature (70°C). To compensate the pressure losses it had to be compressed. The mass flow of the recycled syngas was set to a value where a mixture temperature of 500°C was achieved. The flue gas

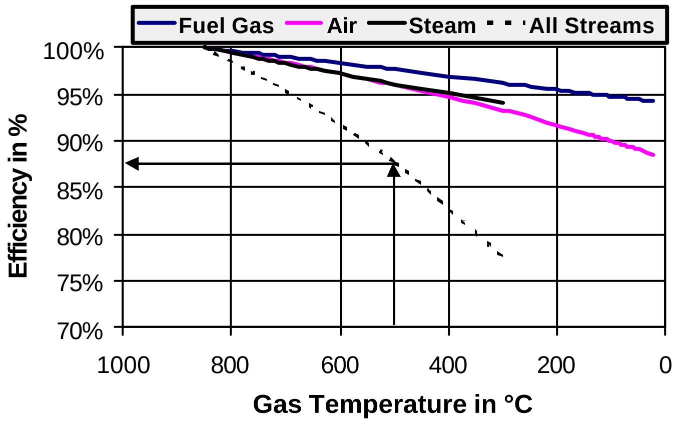


Figure 2.7-2 Influence of stream temperatures on the efficiency

from the heat supply of the gasifier was mixed with the exhaust gas from the gas engine. A temperature of 513°C was obtained. The flue gas from the gasifier had to be throttled to a pressure of 1.46 bar). Five high temperature heat exchangers were omitted this way.

The operating conditions of the gasifier were a temperature of 850°C, a pressure of 3.7 bar and a char conversion rate 4%C/min that resulted in a char amount in the fluidised bed of 12%wt. The mass flow of the biomass was 0.23 kg/s, of the steam 0.18 kg/s and of the air 0.07 kg/s. The pressure drop over the gasifier was 459 mbar. In Table 2.7-2 the composition of the gas was shown. The higher heating value of syngas depended on the moisture content in the syngas. Directly after the gasifier a HHV of 6.74 MJ/STDm³ was obtained. As the gas

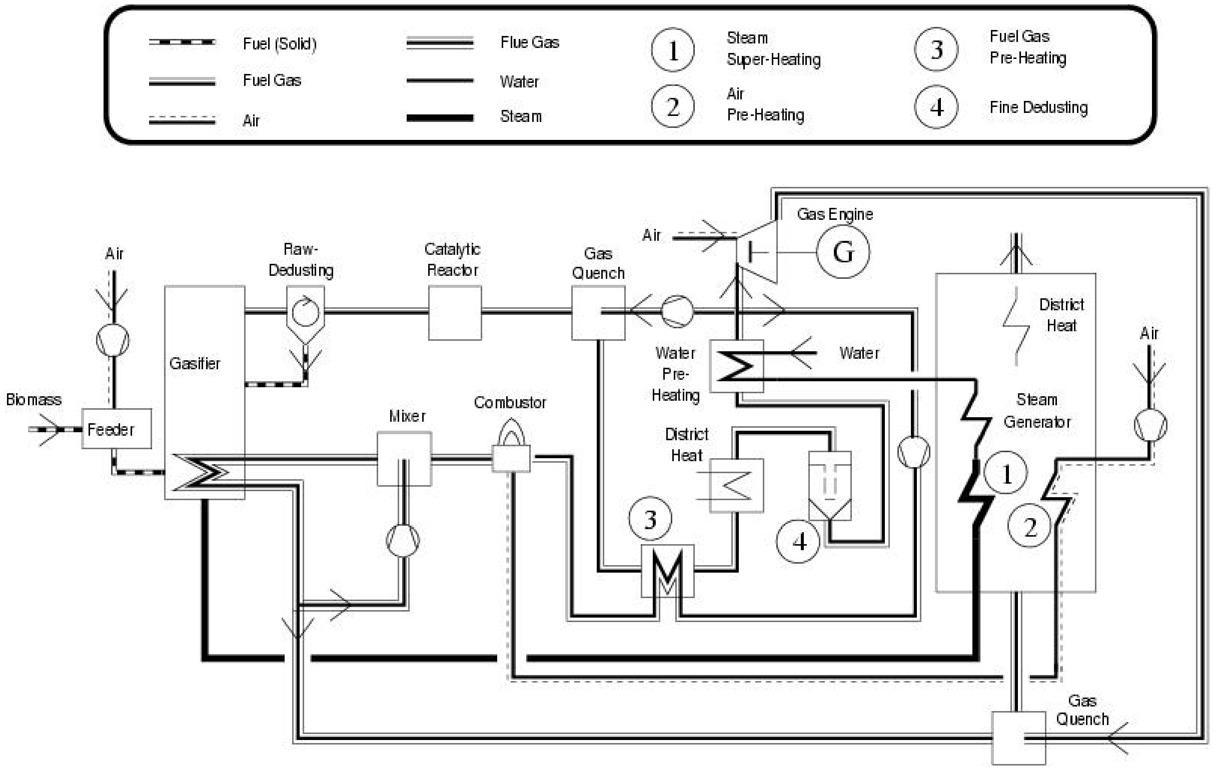


Figure 2.7-3 Economically optimised concept

Table 2.7-2 Gas composition

Component	H_2O	CO	CO_2	H_2	CH_4	C_2H_2	C_2H_4	C_6H_6	C_7H_8	N_2
%vol	41.64	16.03	9.48	15.35	7.25	0.43	1.20	0.27	0.00	8.35
%wt	36.35	21.76	20.21	1.50	5.64	0.54	1.63	1.03	0.00	11.34

had to be cooled down to a temperature of 70°C the value increased to 10.50 MJ/STDm^3 before the engine. If totally dried a maximum value of 11.72 MJ/STDm^3 could be reached. Through the water condensed during the cooling the fresh water supply of the gasification unit was reduced to 0.03 kg/s. An energy balance of the gasifier is shown in Table 2.7-1. An energetic efficiency of 94.2% and a cold gas efficiency 99,8% were achieved. Losses depicted in Table 2.7-1 are heat losses to the ambit. The gasifier was supplied with 743 kW heat by the heat exchanger. Thereby the heat for reaction, heat losses and the heating of bed material / biomass was included multiplied with a safety factor to have a firm basis. Hence, the heat losses in Table 2.7-1 were higher than necessary.

Table 2.7-1 Energy balance of the gasifier

	Input			Output	
	kW	%		kW	%
Biomass	3905	74.08	Syngas	4969	94.25
Steam	609	11.55	Heat losses	303	5.75
Air	15	0.28	Sum	5272	100.00
Heat supply	743	14.10			
Sum	5272	100.00			

The inlet temperature of the flue gas into the heat exchanger for the heat supply was 1100°C, the outlet temperature 900°C. A mass flow of 2.72 kg/s was required. Due to the high inlet pressure of 5 bar the pressure drop was only 24 mbar. For further specifications see chapter 2.5.4.4. Pressure drop of the cyclone was 0.1 bar and of the fibre filter 0.20 bar. The pressures were calculated backwards starting with the engine where a pressure of 3 bar was required.

In Table 2.7-3 the energy flows of the gasification unit were depicted. 25.6% of the biomass input was converted to electrical energy. About 18% of the input could be used for district

Table 2.7-3 Energy flows of the gasification unit

Energy balance of the gasification unit			Specification of the losses			Energy for compressors		
	kW	%		kW	%		kW	%
Biomass	3905	100.00	All losses	2203	100.00	All compressors	117.7	100.00
Engine (net)	1000	25.60	Gas Engine	809	36.74	Air Feeder	14.9	12.67
District heat	703	17.99	Flue Gas	524	23.81	Air Combustion	77.1	65.52
Losses	2203	56.41	Gasifier	303	13.77	Syngas Combustion	10.4	8.79
			External Cooling	507	23.01	Syngas Quench	10.7	9.13
			Others	59	2.67	Water	0.1	0.08
						Flue gas for heat supply	4.5	3.81

heating. This resulted in an overall efficiency of 43.6%. The amount of losses was high and, therefore, they were specified. 36.7% of the losses were caused by the gas engine through cooling and further losses. The flue gas was leaving the unit with a temperature of 100°C and was responsible for 23.8% of all losses. 303 kW respectively 13.8% of the losses were caused by the heat losses of the gasifier. A high amount of 507 kW could not be recovered from the syngas cooling from 105°C down to the engine inlet temperature of 70°C. During this cooling a high share of the moisture contained in the syngas condensed. As no stream in the gasification process had the capability to assimilate the high amount of energy in this small temperature range the energy had to be discharged to the ambit. Several compressors were needed. Overall the required energy for compressing amounted to 117.7 kW that had to be provided by the generator of the gas engine. The reason why no higher overall efficiency was achieved could be found in the nature of the allothermal steam gasification. First, the allothermal gasification required a heat source from outside the gasification process. Therefore, syngas was combusted. The flue gas from the heat supply and the syngas from the gasifier have much more thermal energy than recoverable for the process. The reason for this was, second, steam was used as gasification agent. A lot of energy was necessary for the steam generation and it was not possible to recover this energy. A solution would be the integration of a steam cycle in addition to the gas engine like applied in an IGCC (Integrated gasification combined cycle). However, the small scale of this decentralised gasification unit did enable this application under economical conditions, furthermore, the objective of the gasification unit was the generation of district heat.

2.7.6 Heat Exchangers

The heat exchangers required for the heat recovery were engineered. Generally, shell and tube heat exchangers were taken. The design, heat transition coefficient and the pressure losses were calculated following the guidelines of the "VDI Wärmeatlas", a standard for heat exchanger design in Germany. All heat exchangers operate in counter-current mode with a one tube pass. Baffles were used to enhance the heat transfer coefficient inside the shell. The tubes were triangularly arranged. The steam generator had to be placed vertically, all other heat exchanger horizontally.

3 Results and Conclusions

3.1 Results

3.1.1 Biomass Procurement and Fuel Preparation (Kungl Tekniska Högskolan & University of Essen)

Three biomass raw materials (straw pellets, salix, birch wood) were selected and supplied as chips or pellets for use in the project. The fresh wood chips still had a high moisture content and had to be dried before use. The drying procedure includes oven-drying at 105 °C followed by open storage to reach equilibrium moisture content with the surrounding air. For the LDU it is necessary to mill and sieve the biofuels, through which the fraction of particle size 1.0-3.2 mm is obtained.

For the pilot plant the fuel preparation process can be simplified. Through a good storage facility the biomass can be dried (cold) up to a moisture content of 20 %, which is sufficient enough for the process. The matrix below shows major lines of handling for supplying a gasifier:

$$\text{Harvesting} \Rightarrow \begin{array}{c} \text{Storage} \rightarrow \text{Transport} \rightarrow \text{Chipping} \\ \text{Storage} \rightarrow \text{Chipping} \rightarrow \text{Transport} \\ \text{Transport} \rightarrow \text{Storage} \rightarrow \text{Chipping} \\ \text{Chipping} \rightarrow \text{Transport} \rightarrow \text{Storage} \end{array} \Rightarrow \text{Gasification}$$

If the last alternative among the supply-chains is chosen the wood chips may be used in many modern gasifiers directly without any pre-treatment.

3.1.2 Gas Quality Optimisation (Kungl Tekniska Högskolan & University of Essen)

All 40 air and 20 steam gasification tests were performed and completely evaluated. All light tar samples were analysed, and also the heavy tar analysis is finished. The gasification tests for both gasification agents have shown an increase of the H_2 and CO yield of the product gas at increased temperatures. Steam gasification provides the highest hydrogen contents per kg biomass. However, it must be considered that steam gasification has the lowest biomass throughput, if no oxygen is supplied to the process. Maximum methane yields were

Table 3.1-1 Gasification conditions for different gasification modes

Steam gasification	0.1-0.5 MPa; 750 – 850 °C, olivine sand , all biomasses with low to medium ash content (woody fuels), straws limited in use, separate tests required. Dry LHV 9-11 MJ/m_n^3 , up to 42 %vol. H_2, 120 g_{Tar}/kg_{Fuel}
Air gasification	0.1-0.5 MPa; 850 - 950°C, olivine sand, Dolomite, all biomasses with low to medium ash content (woody fuels), straws limited in use, separate tests required Dry LHV 5-8 MJ/ m_n^3 , <10 %vol. H_2, ≈ 30 g_{Tar}/kg_{Fuel}
Air / steam gasification	0.1-0.5 MPa; 750-900°C, olivine sand, all biomasses with low to medium ash content (woody fuels), straws limited in use, separate tests required. Dry LHV 7-9 MJ/ m_n^3 , <15 %vol. H_2, ≈50 g_{Tar}/kg_{Fuel}

observed at temperatures between 840 – 875 °C. It turned out that the bed material "olivine sand" had the best properties for all tested biomasses concerning sintering, indelibility and entrainment.

Based on the experiments described above, we are able to deliver a set of parameters for stable operating conditions for the gasifier process (see Table 3.1-1).

3.1.3 Selection and Optimisation of a Suitable Mixture Formation Concept (Technical University Graz & Jenbacher AG)

- If mixture formation is by a tubular gas feed in the inlet pipe (shortly before the inlet valves) then this sets up a highly inhomogeneous mixture distribution in the combustion chamber.
- Even a gas feed via disc valves could achieve no detectable improvement, quite apart from the other disadvantages.
- The best mixture quality is achieved by an annular gas feed into areas of high air speed (similar principle to the Venturi mixer).
- Air/gas mixing by taking a gas feed via a mixing chamber directly into the combustion chamber is not beneficial. Apart from the highly inhomogeneous mixture in the combustion chamber for this design, the air/fuel ratio in the chamber lies outside the ignition limits, so that the spark plugs could not be located in this chamber.
- A pre-requisite for thorough mixing is to achieve the maximum possible interactive surface area between the methane and air.
- The more time available to the components (gas and air) for thorough mixing, the better the homogeneity.

Another important parameter is turbulence. This is why it is best to inject at high speeds, or to feed the gas at points where high turbulence intensities prevail.

3.1.4 Recalculation of the Most Promising Mixture Formation Concept (Technical University Graz)

The detailed construction (made at Jenbacher) of the mixture formation concept was recalculated with 3D-CFD methods in order to gain insight view into the processes of mixture formation. Basing on these results the construction can be optimised. Further first information about the valve timings of the blow-in valve can be obtained.

3.1.5 Performance tests of the new mixture formation concept (Technical University Graz & Jenbacher AG)

Performance tests using a single cylinder research engine were made. The results were very promising. Only minor differences in efficiency compared to the reference concept occured. No differences in knock and emission behaviour could be stated.

3.1.6 Measurement of the thermal conditions at the spark electrodes (Jenbacher AG)

In order to obtain parameters concerning the temperature stress, the temperature of components in the mixing chamber (the present pre-chamber) have been measured. The surface temperatures were between 900 and 980°C. This temperature level was more than 200°C above the expected temperatures. For H_2-rich fuels this means that the cooling of the components has to be intensified and improved.

Main results:

With this results we must change the first concept of a cylinder internal mixing chamber. To avoid auto- ignition the only possible concept for the use of H_2-rich gases with high temperature and pressure is a so called direct ignition combustion system.

3.1.7 Selection of a series hot gas valve, Fa. Hoerbiger (Jenbacher AG)

According to the latest findings the engine performance decreases linearly with increasing gas temperature. With the company Hoerbiger we are making the exact calculations for the dimensioning of the hot gas valve (this type was a prototype for another use). The free gas diameter guarentees. by calculating with an indicated speed of 1.500 min-1 and a heating value of 5.3 MJ, a BMEP of 10 bar. The resulting cylinder performance then amounts to about 80 kW. According to Fa. Hoerbiger the valve can be used safely up to a gas temperature of 100°C, for temperatures higher than 100°C the actor would have to be separated from the hot part of the valve and then be connected by a coupling element.

3.1.8 Conception of a special test version cylinder head (Jenbacher AG)

Proceeding from the best solution for an internal mixture formation, rooted in the CFD calculations, the constructive realization was worked on within the scope of a project work at the HTL at Steyr (school for engineers with graduation). To test the cylinder head on the single cylinder research engine resulting from the task, the Version C (series production up to 7/1999) was chosen. This design of the cylinder head is similar to that of the version which is in series right now, concerning the inlet and outlet ports. Thus, after the successful termination of the experiments the found solution can directly be transferred to the latest cylinder head design. The first step of the geometric interpretation will be to determine the essential diameters of the gas inblow valve. These values are limited on the one hand by the low heating value (LHV), the gas temperature, by the existing pressure and by the maximal possible BMEP (engine load) of the engine. On the other hand the requirement to install the produced solutions into a fixed design of the cylinder head through diverse adjustments of the geometric design, i.e. a cylinder head optimized according to all boundary conditions, is not possible because of the costs (the expense of a new model is at least 100.000,- EURO). In team work with the supplier of the hot gas inblow valve (Fa. Hoerbiger Ventilwerke) the optimal size of 30 mm (type MV 30) was confirmed.

3.1.9 Conception of a new series production cylinder head with an included hot gas valve (Jenbacher AG)

In the final stage of the Jenbacher program we designed together with HTL-Steyr a possible series solution for the new cylinder head.

3.1.10 Investigation of the Gasifier (University of Essen)

The gasifier was thermodynamically optimised. Though the fuel gas quality was the best at high temperatures it was more effective to gasify at low temperatures because of the amount of heat required for the gasification process. Thereby, the mass flow of the gasification agent (steam) should be as low as possible. The pressure had almost no impact. For the heat supply to the gasifier a concept was chosen where a share of the produced gas was combusted with pre-heated air. The hot flue gas with a temperature of about 1100°C was fed to a heat exchanger that was situated in the fluidised bed. The heat exchanger was engineered. The scaling of the gasifier showed that only geometrical similarity was achievable. The gasifier was optimised: 1) The ratio of height to diameter of the fluidised bed, 2) The freeboard height, 3) The bubble distributor, 4) The ash distraction and 5) The hot gas filter system. Calculated stable operating conditions were achieved. The size of the gasifier was estimated. A suitable insulation was found.

3.1.11 Feeding Tests (University of Essen)

For the feeding of biomass into a pressurised gasifier pneumatic conveying was necessary. Due to the problematic conveying behaviour of biomass, an injection feeding system was chosen. Within this project two different kinds of feed have been tested, pellets and wood splinters. The feeding of pellets caused no problem, however, the wood splinters did. They showed an enormous bridge-building behaviour. Conclusions: 1) The feed should be as dry as possible, 2) Movable parts in the feeding system should be avoided. Tests with a screw feeder failed and the application of a cell wheel sluice was doubtful and 3) Feed with bridge-building tendency could be transported if it was mixed with pellets or bed material. The mixing ratio depended on the particle size of feed as well as admixed material.

3.1.12 Concept of the Gasification Unit (University of Essen)

Taking into account the results from the previous tasks a thermodynamically optimised concept for the gasification unit was set-up. To achieve a good overall efficiency a complex heat integration was necessary. All streams leading to the gasifier and to the combustor should have a high temperature to reduce the consumption of syngas for the heat supply of the gasifier. A large number of high temperature heat exchangers were required to recover the heat. As one task was the simplification of the concept due to ecomomic aspects the number of heat exchangers and the operating temperatures were reduced. Suitable heat exchangers were selected and engineered for the steam generation and superheating, the air pre-heating, the re-heating of the syngas for the heat supply of the gasifier and district heat generation.

3.2 Conclusions

Based on the experiments described above, a set of parameters for stable operating conditions for both gasification technologies are delivered. The test results show that the highest hydrogen contents were obtained with steam gasification, but with very high tar amounts. The totality of the made gasification tests shows that it is very helpful to admix oxygen to allothermal steam gasification. This enhances the pure steam gasification process in two important ways. It lowers the tar content to values that make the tar cracking more feasible and the fuel throughput is increased. The lowest tar contents were measured in the air gasification tests. The low hydrogen yield of air gasification could be increased through admixing of steam and through the use of a tar cracker.

The use of olvine-sand as bed material was possible without any restriction due to temperature and pressure. Magnesite was limited to high temperature and the use of gasification agent air. At low temperatures around 400-500°C it showed tendencies to build hydroxides which led to agglomeration of particles. Dolomite had similar problems at a pressure of 10 bar with the gasification agent steam in combination with temperatures above 700°C. Hydrogen was a strong catalyst poison over 650°C for dolomite.

The work was successful and brought new approaches to Jenbacher AG which are of interest also to running series developments. The intensively cooled prechamber, which was developed especially for the direct gas inblow, is already produced in series. The proceedings with the inblow of natural gas into the inlet runner has been very promising due to the first tests on the test bench. Nevertheless it has to be further optimised to be produced in series and to take over the place of the recent gasmixing concept in operation. It seems as well, that, due to the knowledge up to now, with this concept a bmep of at least 8 bar is to be reached with biogas. These 8 bar bmep result to a performance of about 750 kW with a 12 cylinder engine, pursued was a performance of 700 kW at the project definition.

In cooperation with Jenbacher AG, the Technical University Graz had developed a very promising method of mixture formation. In a concept study performed with CFD it was shown that gas feeding through a pipe in the intake port makes little sense with regard to mixture formation. The concept of blowing the gas in via two pipes through the open intake valves during the intake cycle proved to be even less favourable. Direct feeding of the combustion gas into the combustion chamber with a mixing chamber proved to be unsuitable as the fuel-air mixture at the spark plug position is far too rich to be ignited at ignition timing. The most suitable concept proved to be the method of blowing the gas in through two rings located immediately before the intake valves on the circumference of the intake port. This concept was implemented. Test bed tests have shown that the new concept is nearly equivalent to the ideal basic version in terms of efficiency, emission behaviour and engine stability.

The gasification of biomass with steam offers advantages regarding the gas composition and the heating value. However, a high technical effort was necessary for the heat supply to the gasifier and for the heat recovery. To reduce the effort with regard to economic aspects the operating temperature for the heat exchanger equipment was lowered and consequently the number of heat exchangers decreased. The attained electrical efficiency was about 25%. The overall efficiency of the CHP unit was about 44%. This relatively low value was caused by the high amount of energy required for steam generation which could not be recovered to the process or be used for district heat generation. The district heat generation was done at a high temperature level. If the emphasis of such a plant would be the electricity generation than the district heat generation could be replaced by a small steam cycle. Due to the allothermal gasification the gasifier was supplied with heat through the combustion of the produced syngas. About 18% of the syngas was combusted for it. If an external high temperature heat source could be integrated for the heat supply to the gasifier the efficiency of this unit would increase significantly.

4 Exploitation Plans and Benefits

Exploitation of the technology is carried out mainly by the industrial partner. Jenbacher AG is one of the market leaders in the gas engine business. The investigated technology can also be used for natural gas applications. The intensively cooled prechamber, which was developed especially for the direct gas inblow, is already produced in series. The first results of the new gas feeding system are good, may be this concept will be used for commercial gas engines too. At the first tests this gas feeding system is operating with natural gas as well because it did not reduce the efficiency of the gas engine as the test have shown. A potential market for the biomass fuel driven gas engines is seen in small decentralised units in the range of a few MW_{el} in Europe as well as in developing countries.

The partners obtained detailed information about the advantages and disadvantages of steam as well as air blown biomass gasification and about the specific problems concerning the use of biomass fuel. The results will be used for research in forthcoming projects.

The dissemination strategy is to continue with the development, to publish results of the investigations in order to indicate the prospects of the biomass technology and to offer this technology to the market. This will be done mainly by presenting results at forthcoming international European conferences and work-shops on biomass utilisation. Furthermore, the University partners will integrate the results of this project in their education and training programme in particular for engineering students.