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HIGH PERFORMANCE GASIFICATION WITH THE TWO-STAGE GASIFIER

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ABSTRACT: Based on more than 15 years of research and practical experience, the Technical University of Denmark (DTU) and COWI Consulting Engineers and Planners AS present the two-stage gasification process, a concept for high efficiency gasification of biomass producing negligible amounts of tars. In the two-stage gasification concept, the pyrolysis and the gasification processes are physical separated. The volatiles from the pyrolysis are partially oxidized, and the hot gases are used as gasification medium to gasify the char. Hot gases from the gasifier and a combustion unit can be used for drying, air preheating and pyrolysis, hereby very high energy efficiencies can be achieved.

Encouraging results are obtained at a 100 kW_{th} laboratory facility. The tar content in the raw gas is measured to be below 25 mg/Nm³ and around 5 mg/Nm³ after gas cleaning with traditional baghouse filter. Furthermore a cold gas efficiency exceeding 90% is obtained.

In the original design of the two-stage gasification process, the pyrolysis unit consists of a screw conveyor with external heating, and the char unit is a fixed bed gasifier. This design is well proven during more than 1000 hours of testing with various fuels, and is a suitable design for medium size gasifiers.

Keywords: biomass conversion, fixed bed, gasification, pilot plant, pyrolysis, straw, tar removal, wood chips

1 INTRODUCTION

At the Technical University of Denmark (DTU), the fundamental processes of gasification: pyrolysis, partial oxidation and gasification, have been studied for more than 15 years.

The objective of the research was to study and develop biomass gasification processes with a high energy efficiency and low environmental impact. In the 1980ies and the early 1990ies, the focus was on gasification of straw which is a major energy resource in Denmark, but recently wood and other fuels have been investigated.

The studies at DTU document that:

When the pyrolysis and the gasification processes are physically divided by a zone where the volatiles are partially oxidized, the content of tars in the produced gas is dramatically reduced [3] and the gasification process is easy to control. Further, only the part of the gasifier where the volatiles are being partially oxidized require high temperature material, and the tendency of agglomeration is reduced substantially [4].

When the produced gas has a very low content of tars, the gas cleaning system becomes very simple and reliable [5].

When fluegas and hot product gas is used for air preheating, drying and pyrolysis, the coldgas efficiency can exceed 90%, based on LHV. [6].

Gas produced on a two-stage gasifier is a good fuel for internal combustion engines, with high efficiencies and low emission of NO_x and UHC [7].

Gasification with steam gives high reaction rates [8], reduces the amount of soot particles [9] and results in a gas with high H₂ content and lower CO content.

While passing through the char bed, the tar content in the gas is further reduced [10].

are separated into two different reactors. The biomass is fed into the pyrolysis zone, where it is heated. Hereby biomass will decompose into char consisting of carbon and ashes, and volatiles consisting of gasses and tars.

The heat for the pyrolysis process can be added from an external heat source, increasing the total efficiency of the gasification plant by 10-20%. The volatile products from the pyrolysis are partial oxidized, whereby the temperature of the gases increases and the amount of tars is significantly reduced. The hot gases from the partial oxidation reactor and the char from the pyrolysis reactor is led to the gasification reactor, where the char reacts chemically with steam and carbon dioxide producing H₂ and CO. The amount of tars is further reduced as the gas flows through the char-bed. The produced gas is cooled and cleaned, and exceeding water vapor can be condensed.

When the moisture content in the fuel is below 20-25%, the process is water consuming, and all the condensate can be led back to the process as gasification agent. If the moisture content in the fuel is above 25% the process will produce condensate. Since the tar content is extremely low, the condensate from the two-stage gasification process is so clean, that it can be led to the public sewer.

After gas cleaning, the gas is led to an internal combustion engine, which produce electricity and heat. The flue gas and the hot product gas can be used for air preheating, drying and pyrolysis.

The result is a process having a high energy efficiency, low environmental impact and which produces a gas with an extremely low tar content and a relatively high specific heating value.

2 THE TWO-STAGE GASIFICATION PROCESS

The two-stage gasification process has its name because the pyrolysis process and the char gasification

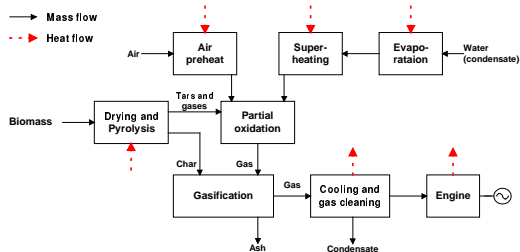


Figure 1: Diagram of the two-stage gasification process

Integration of the heating- and cooling processes can be designed in different ways. The product gas leaving the gasifier is about 800°C, and the exhaust gas from the engine is between 450-600°C depending on the fuel/air ratio, compression ratio etc. Tests and development of the two-stage gasification process have led to a robust design, where the pyrolysis unit is an externally heated screw conveyor, and the char is gasified in a fixed bed. Due to a very low tar content in the gas, the particles can be separated from the gas in a bag filter, see Figure 2.

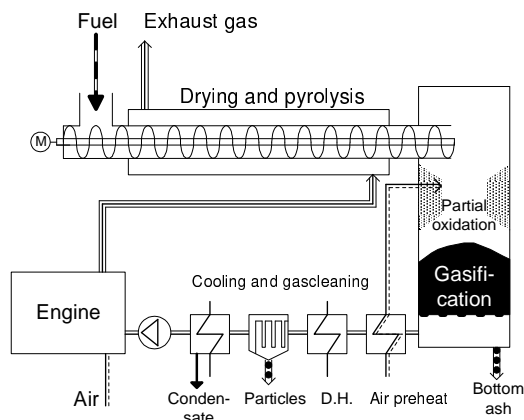


Figure 2: Layout of the two-stage gasification process, with externally heated pyrolysis unit and fixed bed char gasification

3 TESTING THE PROCESS

Two stage gasifiers have been successfully fuelled with straw, woodchips and briquettes. The two-stage gasification process has now been tested and verified for more than 1000 hours.

3.1 5-kW plant (1988-1989)

The first test rig consisted of a piston feeder for straw, a pyrolysis unit, partial oxidation of the volatiles, a fixed bed char-gasifier and gas cooling. Pyrolysis, preheating air, evaporation and superheating were electric. The test rig was controlled manually. The 5-kW two-stage gasifier had totally 50 operating hours, gasifying straw.

The results from the tests were primarily to demonstrate the process and to verify that the tar content was very low compared to other gasifiers. Further, it was demonstrated that the energy efficiency was high [11, 18].

3.2 50-kW plant (1989-1992)

Based on the encouraging results obtained on the 5-kW plant, a pilot plant with a thermal input of 50 kW was built. The 50-kW plant consisted of a piston feeder for straw, a pyrolysis unit, partial oxidation of the volatiles, a fixed bed char gasifier, gas cooling, venturi scrubber system for gascleaning and an IC engine.

The exhaust gas from the engine was not integrated in the process. The following processes were still electrically heated: the pyrolysis unit, the air-preheater, the evaporator and the superheater. The plant was controlled manually.

The results with the 50-kW gasifier confirmed the 5-kW tests. The tar content was low, and the energy efficiency was high. In addition, the gasifier was easy to control, because all heat-releasing processes takes place in the gas phase — by partial oxidation — which means that the maximum temperature is easy to measure and also easy to regulate by means of the air addition [4].

It was experienced that bridging and channelling did not happen in the char reactor, which often is a problem with other gasification processes. The reason for this is that all chemical reactions in the char bed are endothermic.

The engine was mostly running well, but problems with backfiring were observed.

The 50-kW two-stage gasifier had a total of 300 operating hours.

3.3 400-kW pilot plant (1992-1996)

Based on the promising results from the tests with the 50-kW gasifier, a co-operation with the company REKA A/S was established. The purpose was to upscale the two-stage gasification process to 400 kW.

The plant consisted of the following main components: Wood chip feeder, pyrolysis unit heated by exhaust gas, air preheater heated by product gas, partial oxidation chamber, fixed bed char gasification chamber with grate, ash conveying system, evaporator and superheater heated by exhaust gas, spark ignition (SI) engine generator system, automatic control and monitoring.

Unfortunately the plant had several trivial problems, such as problems with software and hardware in the computers, airtight valves were leaking, and there were construction errors in the main components.

As with earlier two-stage gasifiers, the results showed that the produced gas had a low tar content, the process had a high energy efficiency, and that the system was stable and easy to control. Beyond these results it was shown that the engine was operating without problems, the efficiency of the engine was as expected, the exhaust gas from the engine was used to heat the pyrolysis unit, the evaporator and the superheater, and the produced gas was heat exchanged with air without problems [12].

The 400-kW two-stage gasifier had a total of 400 running hours, hereof 100 hours with the engine running.

3.4 100-kW test plant (1995-present)

A two-stage gasification plant, with a thermal input of 100 kW, was built at DTU. The purpose of this plant was originally to support the development of the 400 kW plant.

The plant were therefore built very flexible, so it is possible to vary and measure many parameters. It consists of following components: Propane heated pyrolysis unit,

partial oxidation zone and char gasification reactor built of firebricks, movable grate, chamber for ashes, gas cooler, gas cleaning system and an SI engine. Air-preheater, evaporator and superheater are electrically heated. The plant has two feeding systems: one for wood chips and one for pellets/briquettes.

So far, the 100 kW gasifier has had more than 400 operating hours.

Intensive research has been carried out on the 100 kW two-stage gasifier. Most tests were made with wood chips and the two-stage gasification process is now fully verified when fuelled by wood chips. The most important results obtained on the 100 kW gasifier are presented in this paper.

In 1999, all processes in the two-stage gasification process had been investigated, and technical solutions found for all the processes. It was concluded that the future work in the development and commercialisation of the two-stage gasification process should be up-scaling and long-term testing of materials. A co-operation between DTU and COWI A/S was established in order to upscale and commercialise the process, and the establishment of a continuously operating 80 kW two-stage gasification plant was initiated.

The further work on the 100 kW two-stage gasifier will be testing other fuels.

3.5 80-kW pilot plant (2002-?)

The promising results obtained on the 100 kW two-stage gasifier resulted in the conclusion in 1999 that the process was now fully demonstrated, and the future work will be up-scaling and long-term experience. It was decided that a small continuously running test plant should be built at DTU. The plant should be small (60-100 kW), in order to keep expenses for hardware and fuel low.



Figure 3: 80-kW pilot plant at DTU

The erection of the plant has finished and it is currently being commissioned. It consists of the following components: Automatic feeding system for wood chips, pyrolysis unit heated with exhaust gas from the engine, partial oxidation zone and char gasification reactor with movable grate and ash transport, product gas coolers for exhaust gas, air preheat and heat supply of building, gas cleaning system and an SI engine. The plant is equipped with an automatic control system, and can run unmanned.

4 TEST RESULTS

During the period 1996-1999, several tests were performed on a 100 kW two-stage gasifier at DTU, with woodchips, briquettes and pellets as fuels. In 1998, the gasifier was optimised as regards tar reduction and energy efficiency [6].

Results obtained from tests with the 100 kW gasifier are presented below.

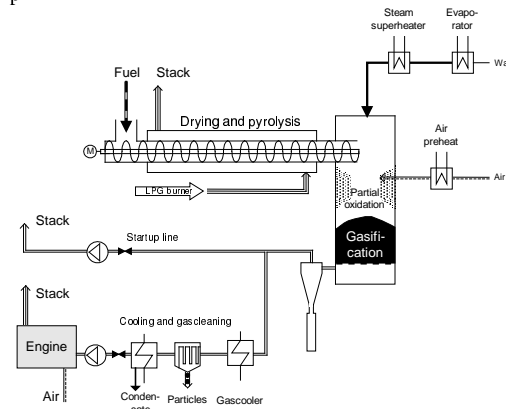


Figure 4: Schematic layout of the 100 kW two-stage gasifier at DTU

In Figure 4 a schematic layout of the 100 kW two-stage gasifier is illustrated. The separate process steps: heating of pyrolysis unit, air preheat, evaporation and superheating of steam, can be regulated independently.

4.1 Tar measurements

Several institutions have measured the tar content in the raw producer gas. The tar content in produced gas, before any gas cleaning is low, see Table 1.

Table 1: The tar content in the produced gas after the gasifier before gas cleaning

	Method	Date	Tar content mg/Nm ³
Danish Technological Institute, Denmark (TI)	Gravimetric	23 Nov. 1999	25
		24 Nov. 1999	25
	GCMS	23 Nov. 1999	5
		24 Nov. 1999	25
The Technical University of Denmark (DTU)	GCMS	9 Sept. 1998	16
		10 Sept. 1998	3
	GCMS	23 Nov. 1999	3
		24 Nov. 1999	6
Royal Institute of Technology, Sweden/DTU	Solid phase adsorption (SPA)	8 measurements 23-24 Nov. 1999	5-18 Average 10
Risø National Laboratory, Denmark	GCMS	9 Sept. 1998	16
		10 Sept. 1998	2,5

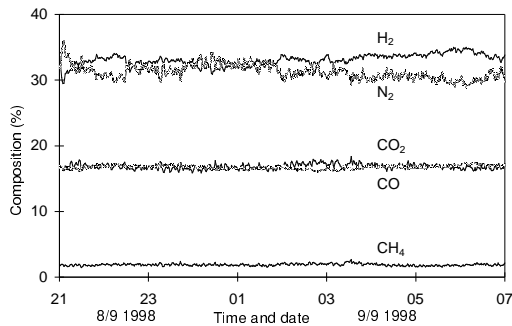
In Table 1, it is seen that the tar content in the product gas is below 25 mg tar/Nm³ [6], [10].

Danish Technological Institute (TI), measured the tar content in the gas after the baghouse filter twice. The results of the two measurements were 4 and 6 mg tar/Nm³ [5].

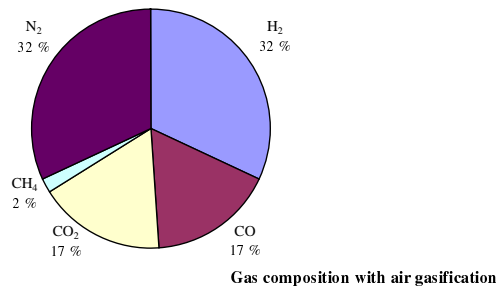
4.3 Gas composition

The composition of the produced gas depends on the amount of water/steam added to the process and the energy efficiency of the plant. When steam is added to the process, more hydrogen will be produced due to water-gas shift reactions. The high content of hydrogen results in a gas with good combustion properties and low emissions. [7], [13].

Highly efficient gasification processes, such as the two-stage gasification process, need less air to gasify the char than other gasification processes, and therefore the content of nitrogen is less than in gas produced on other processes. The result is a better fuel for SI engines.



Gas composition with steam gasification



Gas composition with air gasification

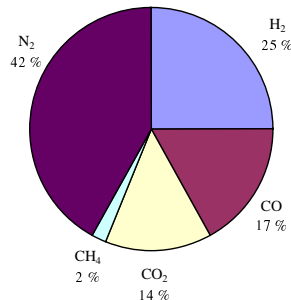


Figure 5: Gas composition of the produced gas from the 100 kW-two-stage gasifier. The upper figure is minute values during a test where biomass-steam ratio (by mass) was 1:1. The average gas composition for this test is seen in the lower left figure. The lower right figure is the average gas composition from a test where steam is not added to the gasifier

4.4 Energy efficiency

Based on the energy content in the fuel, the measured gas flow and heating value of the gas, the cold gas efficiency (energy in cold gas / energy in fuel) is calculated. The cold gas efficiency of the two-stage gasifier is typically between 90-100%, based on lower heating value [6]. Normally, low-tar gasification processes have a cold gas efficiency of about 80%.

4.5 Pressure drop across char bed

Most of the tests with the 100 kW gasifier were made continuously during 3-5 days. Typically, the pressure drop across the char bed evolved slowly and stabilized after about two days. Exceptions from this were a test with wood pellets. The pellets broke into small pieces and dust. Most tests were made with woodchips as the fuel and the fuel/steam mass ratio was 1:1. The pressure drop stabilized at about 2-4 kPa. When briquettes were used, the pressure drop was below 1kPa [14].

The grate seldom needs to be activated, and when the ash on the grate is removed, the pressure drop across the char bed is reduced, see Figure 6.

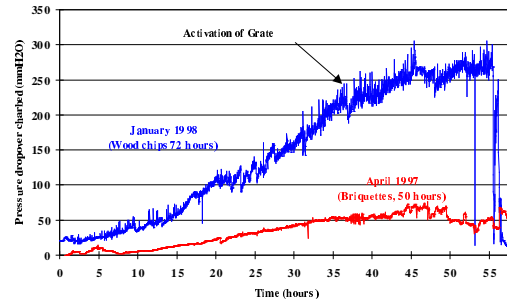


Figure 6: Pressure drop over char bed (mmH₂O) at tests with woodchips and briquettes as fuels

4.6 Gas cleaning

Studies of the particles in the produced gas have documented that the major part of the particles is soot. In reducing atmosphere and high temperatures, soot is formed of the volatiles from the pyrolysis process. The dominant particle size is between 0.2 and 0.5 μm [15]. When the amount of steam is decreased, the amount of particles is increased.

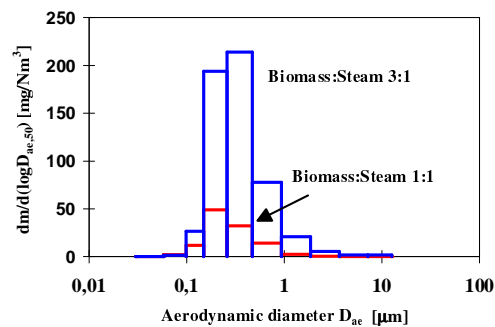


Figure 7A: Size distribution of the particles at different biomass: steam ratios (by mass).

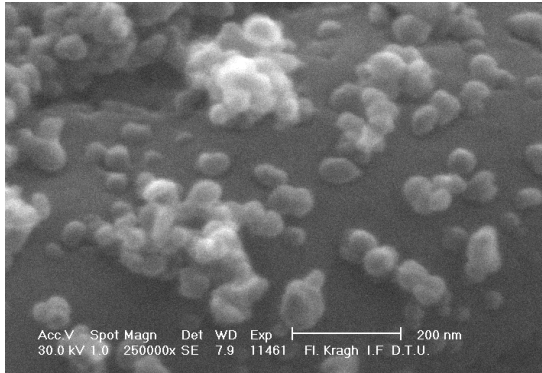


Figure 7B: Scanning Electron Microscope picture of particles collected in the raw gas

When the particles in the produced gas are sub-micron and the tar content is very low, a baghouse filter is a good, cheap and reliable gas cleaning system. Tests with a standard baghouse filter show that the dust on the filter bags is easily removed with back-flush, see Figure 8. The particle load and the tar content after the filter system is around 5 mg/Nm³ [5].

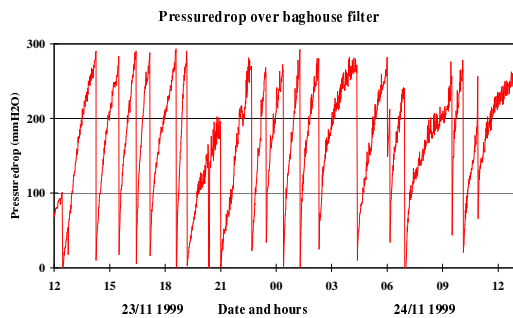


Figure 8: Pressure drop over baghouse filter during test at DTU, November 1999

4.8 Condensate

Investigations of the condensate from the 100 kW gasifier show that it is clean enough to be led to the public sewer without further treatment [16], [17]. The investigations covered inhibition of nitrifiers and content of organic compounds. The content of PAH and other organic compounds is very low in the condensate.

4.9 Straw pellet experiment

A 100-hour test with straw pellets was carried during autumn 2001. The pellets contain additives preventing the ashes from melting and sintering. The main results were that the additive made it possible to reduce the carbon content in the ash from the gasifier and that it did prevent the ash from sintering.

5 NEW DESIGNS OF TWO-STAGE GASIFIERS

DTU and COWI have recently designed novel low-tar gasification concepts, based on the basic principles of two-stage gasification.

The new designs are:

- The "Vortex" gasifier, which is a simple downdraft gasifier taking advantage of an advanced gas flow

pattern. [1]

- The "LOW-TAR-BIG" concept, which is a concept for up-scaling the two-stage gasification process to large units; 5-100 MW_{th}[2]. Patents are pending for the new processes.

5.1 The Vortex gasifier

The Vortex gasifier combines the simple construction of a downdraft gasifier with the low tar output of the two-stage gasifier. By means of a special flow pattern inside the gasifier the tar from the pyrolysis is brought to a hot area above the char bed, where the tar undergoes thermal cracking. This way the tar production from the Vortex gasifier is low compared to ordinary downdraft gasifiers, but without a complex shape of the reactor.

Preheated air is supplied through angled nozzles in a way that a horizontal rotating vortex of air is created. When the rotating air reaches the boundary layer at the top of the char bed, the friction will reduce the radius of the rotational curve. Hereby, a spiral towards the centre of the reactor is created, which is called secondary flow. The secondary flows towards the centre will be present both right on top of the bed and in the upper part of the bed. The hot air flows towards the centre in the top of the bed where it will cause the biomass to pyrolyse, and volatile pyrolysis products are created. In the centre of the char bed, there will be an upward flow of air and pyrolysis products in the centre of the gasification chamber. See [1].

5.2 The LOW-TAR-BIG concept

The LOW-TAR-BIG gasification concept is designed for medium and large scale, high-efficient, low-tar biomass gasifiers. The concept combines the advantages of: 1. two-stage gasification, 2. drying with superheated steam, 3. pyrolysis with superheated steam, 4. gasification with steam and 5. use of standard heat exchangers. Dried fuel, e.g. dried by superheated steam, and steam are led to a pyrolysis unit. The energy for drying and steam generation is transferred in standard heat exchangers where e.g. exhaust gas is cooled.

The LOW-TAR-BIG gasification concept makes it possible to build low-tar gasifiers, where pyrolysis and gasification reactors are fluid beds. Hot steam for pyrolysis can be used as fluidisation medium as well as heat carrier in the pyrolysis unit. Hereby, the two-stage gasification process can be up-scaled to large plants.

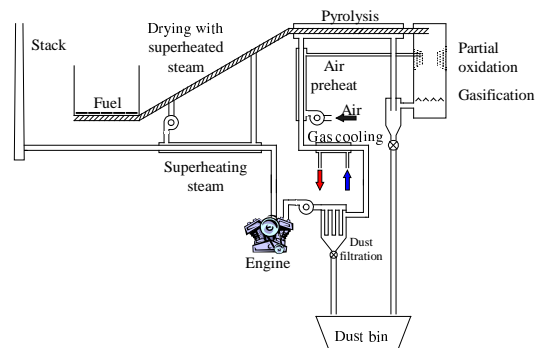


Figure 9A: Example of layout of the LOW-TAR-BIG concept, for medium size (1-10 MW_{th}) low tar high efficient gasification plants

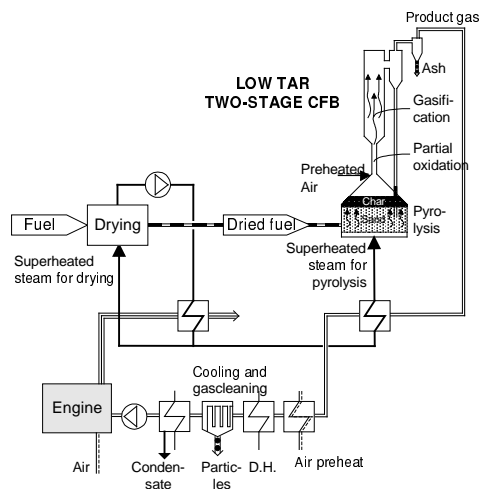


Figure 9B: Example of layout of the LOW-TAR-BIG concept for large plants (>10 MW_{th}) where the pyrolysis and gasification processes are integrated into one fluid-bed reactor. Steam and bed materials are heat carriers for the pyrolysis process

For detailed information about the LOW-TAR-BIG concept, see [2].

6 CONCLUSIONS

All the processes involved in the two-stage gasification process have been investigated experimentally.

The results of the experiments document that

- The two-stage gasification process produces a gas with an very low tar content.
- Use of heat from engine and product gas for drying, pyrolysis, evaporation, steam superheating and air preheating results in a high energy efficiency.
- The two-stage gasification process is stable and easy to control.
- Bridging and channelling has not been observed in the two-stage gasification process.
- Gas engines run well on the produced gas from the two-stage gasification process.
- Gas cleaning can be done effectively and reliably with a baghouse filter, due to the very low tar content in the gas.

The development of the process steps in the two-stage gasification process is considered finished for wood fuels. The next step towards commercialisation is to upscale the process and to obtain long term experience. A 80 kW gasifier is built for this purpose. For gasification of other fuels such as straw, waste etc., further development is still needed.

New designs of gasifiers have been developed, based on the basic principles of two-stage gasification: pyrolysis, partial oxidation of volatiles and char gasification. Two-stage gasifiers can hereby be built as.

- Small and simple fixed bed units
- Medium sized two-stage fixed bed CHP plants
- Large-scale CHP plants

7 ACKNOWLEDGEMENTS

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