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Deliverable 8:
Biomass gasification – State of the art description

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Foreword

The importance of an efficient utilisation of biomass as a renewable energy in terms of global warming and resource shortage are well known and documented. Biomass gasification is a promising CHP technology, due to its high electrical efficiency compared to other CHP systems in the lower and middle range of power. This power class has high potential with respect to heat demand, and hence, biomass gasification is predestined for decentralized energy systems.

Fixed bed gasification is predominantly in this lower power range, since fluidised bed or entrained flow gasification usually demand for higher plant size for economic feasibility. In the last years especially staged fixed-bed gasification technologies have made decisive progress. These results in low tar producer gases, giving advantage to plant availability and simplicity in gas cleaning (economics). Hence, high hopes are pinned on these technologies for a rapid and successful market introduction.

This document present a state-of-the-art technology description of biomass gasification plants in the small and medium range of power (power load 0.1 - 5 MW_{Fuel}) and usage of natural biomass. It contains a characterisation of different gasification principles, description of the respective process chain and demands by the gas utilization. The process chain includes gas cooling and cleaning and in case of need a waste water treatment. With respect to gas utilisation, the focus has been laid to gas engines, since they are highly efficient and readily available on the market.

The intention of the document is to give an overview on the various technologies, which mainly are still in development, and on their technical requirements. Completeness of the information and data provided in the given cases and examples is excluded. Other cases and examples are feasible.

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Table of Contents

1 Introduction

The gasification of biomass with downstream gas engine conversion of the producer gas into power and heat offers a technical possibility for the provision of combined heat and power (CHP) from renewable energy sources in the sense of cogeneration plants.
The process of biomass gasification with a downstream gas engine targets especially the area of decentralized utilization of biomass cogeneration plants. In comparison to cogeneration technologies (CHP) on the basis of combustion systems higher electrical efficiencies and higher electric power to heat ratios are also achieved in the lower power range. A coefficient σ is calculated as the quotient of the electrical and thermal output. Cogeneration plants are measured substantially against these performance figures - biomass gasification cogeneration plants thus offer for the small power range a relatively high electric power output with smaller thermal output, which facilitates a base load classification into short- and long-distance district heating systems.

A successful launch onto the market necessitates compliance with various European directives as well as national laws, regulations, standards, technical guidelines and the erection of biomass gasification plants that are licensable on the basis of legal status. In legal passages a “state of the art” is often defined as follows [e.g. 1]:

> *“State of the art is the state of development of up-to-date processes, facilities, methods of building or operation that is based on pertinent scientific knowledge and whose functional efficiency has been tested and proven. In ascertaining the state of the art particularly those comparable processes, facilities and methods of building or operation are to be drawn upon.”*

Statements about the state of the art can be made with the aid of assessment and specification criteria shown in Appendix 6 of the Austrian Trade, Commerce and Industry Regulation Act [1]. At present, no plants exist that conform to this definition of “state of the art”, since technology is still undergoing development in broad areas. From current data and facts a "state of technical science” can be defined that is composed of data of presently promoted project and process developments, scientific knowledge, as well as a principal characterization of the plant concept.

Figure 1-1 presents the simplified scheme of a general gasification plant with its system components that permits a rough process description. The fuel is normally fed into the gasification reactor via an air-tight closure (exception: open top gasifier). Conversion of the fuel into a producer gas takes place in the gasification reactor on the basis of various gasifier technologies; this will be treated in more detail in later chapters. The processes of drying, pyrolysis, oxidation and reduction take place in the gasification reactor and its auxiliary reactors.

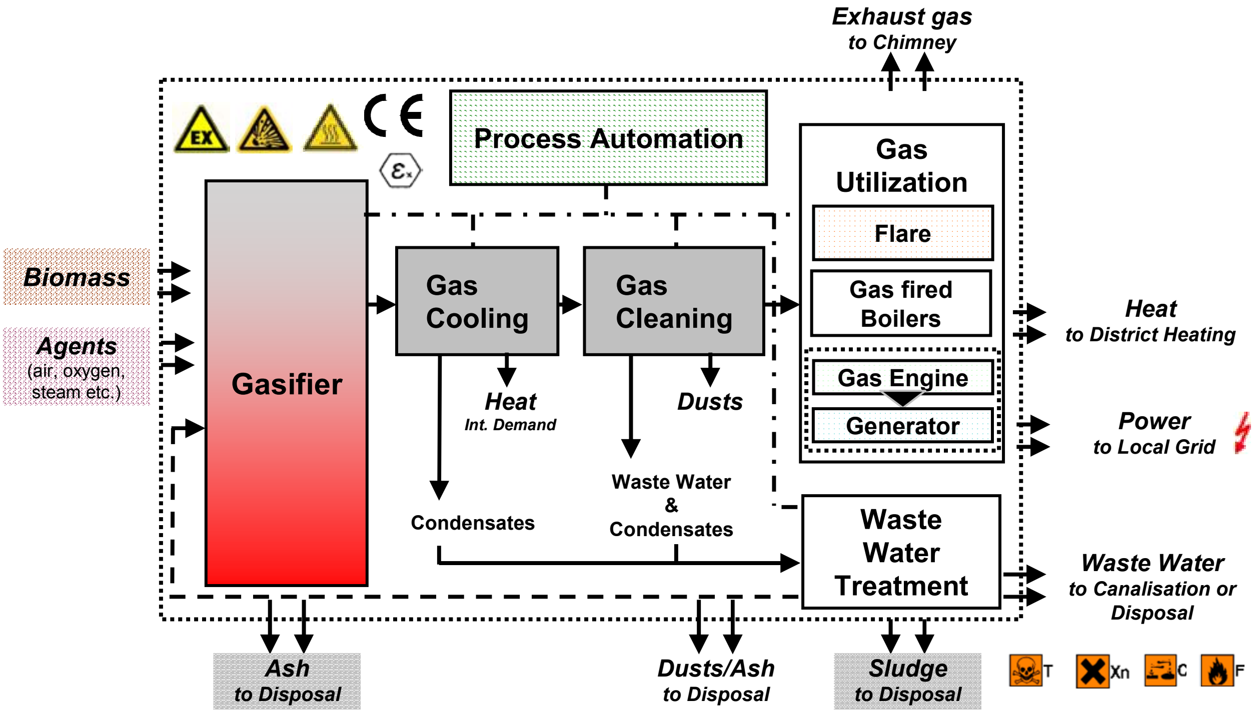


Figure 1-1: Simplified display of a biomass cogeneration plant with gaseous, liquid and solid emission flows [2]

The producer gas leaves the reactor with a certain pollutant load and enthalpy. In the subsequent steps of the process the sensitive heat contained in the producer gas is used for the provision of internal process heat and also for the extraction of heat. In various cleaning and cooling components the producer gas is subjected to a dry (hot) and/or wet cleaning to satisfy the respective cleanliness requirements for later use in a gas-utilization unit (gas engine, gas turbine, micro gas turbine and possibly a fuel cell).

2 Gasification technologies – an overview

The various gasification technologies have advanced on the basis of their history – this chapter will treat the principal manner of operation and the requirements resulting from this.

Various technologies are employed for the gasification of solid fuels. The basic classification of these processes is carried out by considering the basic reactor principles that are applied, i.e.:

- fixed-bed systems
- fluidized-bed systems
- entrained flow systems

All these processes can be operated at ambient or increased pressure and serve the purpose of thermochemical conversion of solid biomass (as a rule unprocessed forest wood chips) into a secondary fuel in a gaseous state, i.e. wood gas or producer gas. For thermochemical conversion it is necessary to supply sufficiently solid biomass and gasification media as well as to provide a pressure and temperature regime by means of suitable gas control and geometrical construction of the reactor. Pure oxygen, atmospheric oxygen or water vapour is used as gasification media. Here the gasification medium fulfils the function of a reaction partner in partial oxidation as well as reduction, which leads to the generation of the producer gas along with drying and pyrolysis processes in the reactor. An important characteristic value that is valid for all gasification processes for any fuel is the degree of cold gas efficiency. This is defined as the ratio of fuel energy used to the chemical energy bound in the cooled and cleaned stream of producer gas (see Equation 2-1). With the aid of this value it is possible to compare the efficiency of various gasification processes.

$$\eta_{CG} = \frac{LHV_{producer\_gas} * \dot{V}_{producer\_gas}}{LHV_{fuel} * \dot{m}_{fuel}} \qquad \text{Equation 2-1}$$

$LHV_{producer\_gas}$ … Low heating value producer gas [kJ/m_n^3]
$\dot{V}_{producer\ gas}$ … Volume flow producer gas [m_n^3/h]
LHV_{fuel} … Low heating value fuel (biomass) [kJ/kg]
$\dot{m}$ … Mass flow fuel (biomass) [kg/h]

The following chapters will primarily treat the technology of gasification in fixed-bed reactors as well as fluidized-bed systems.

2.1 Gasification in entrained flow

With gasification in entrained flow, a fine-grained ground solid – whose grain size is generally smaller than 0.1 mm (10 µm) – is carried through the reactor with the gasification medium and thereby gasified. Possible gasification media, depending on what process is chosen, are auto- or allothermal air or oxygen. The retention time is only a few seconds, and so gasification has to take place quickly at temperatures between 1200 and 1500°C. The high temperatures ensure a complete conversion of the hydrocarbon compounds resulting from pyrolysis of the fuel. The reactivity of the fuel regarding the heterogeneous gas/solid reactions is of secondary importance because the boundary layer determines the speed of the entire process. Pyrolysis and gasification take place at the same time. The ash melts and accumulates after adequate cooling as slag.

2.2 Gasification in a fluidized bed

Fluidized-bed reactors function with a fluidized mix of bed material and biomass. The gasification medium flows in through the nozzle bottom and fluidizes the bed material. This can be inert, as for example quartz sand or also catalytically active with regard to the conversion of organic contaminants in the crude gas through possible after-reactions in the gas phases [3]. For this purpose, substances like dolomite or olivine can be used. The fuel, which is shredded and has a maximal edge length of 50 mm (to 100 mm) is fed into the fluidized or circulating bed. Depending on the degree of fluidization, i.e. inflow speed of the fluidization/gasification medium, one differentiates between a bubbling and circulating fluidized bed. In the case of the circulating type, the bed material removed from the combustion chamber must be precipitated out of the gas stream by a cyclone and then recirculated into the reaction chamber (see Figure 2-1).

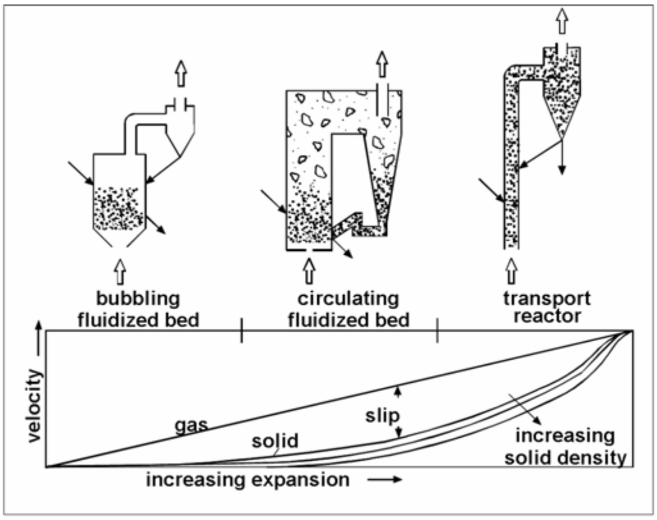


Figure 2-1: Basic systems for gas/solid fluidized-bed reactors [4]

The constant turbulence of the fuel and the bed material (back-mixing) ensures on the one hand that there is a very intensive contact between both, but on the other hand also prevents a similar partitioning into reaction areas as is the case with fixed-bed gasification. The processes of drying, pyrolysis, oxidation and reduction take place in the entire reaction chamber and more or less homogeneously. The constant mixing of reduction and oxidation products with pyrolysis vapours (and thus also the premature discharge of pyrolysis products) takes place through the entire gasification chamber. Disadvantageous to this technology is the higher loading of organic contaminants, tars, and particles, the producer gas compared to e.g. fixed bed systems. A value of up to about 10 g/m_n^3 is indicated for tar load [5, 6] to achieve good gasification results. The temperature level must be chosen as high as possible. However, upper limits are set due to the ash content and ash melting behaviour of the respective fuel. Operating temperatures for ligneous biomass are customarily as high as 950°C [7] and should be reduced down moderately to lower temperatures for i.e. short rotation crops or straw which possess ash softening temperatures of around 800°C.

Two fluidized bed gasification principles are shown in the following. Figure 2-2 shows the fast internal circulating fluidized bed (FICFB) gasification principle, which is realised in a demonstration plant of 8 MW_{fuel} in Güssing (Austria) since 2002. The process consists of to fluidized beds, one for gasification with steam (left) and one for the combustion of a part of the fuel for heating up the bed material, which is internally circulated between combustion and gasification zone [e.g. 8].

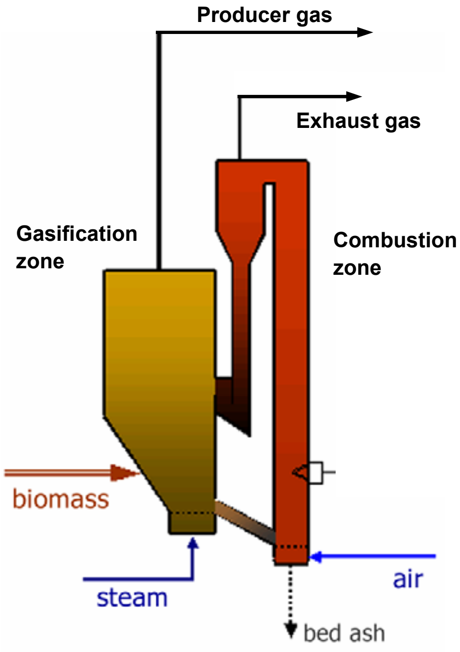


Figure 2-2: Fluidized-bed steam gasification (FICFB) Güssing

A second example for steam fluidised bed gasification technology is the BioHPR (Biomass Heatpipe Reformer), shown in Figure 2-3. In this principle, heat reflux to the gasifier is carried out with heat pipes. It is intended to utilize hot tar loaded gas in fuel cells (SOFC) or micro gas turbines.

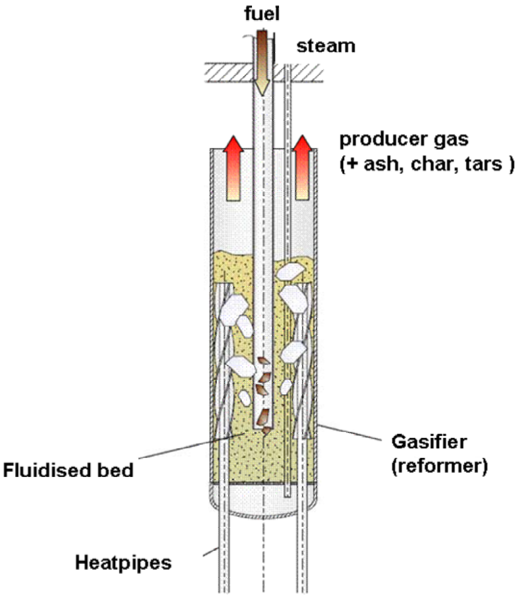


Figure 2-3: Biomass HeatPipe Reformer (BioHPR)

In comparison to fixed-bed gasification, the general primary advantage of fluidized-bed technology is the possibility of up-scaling within wide power load ranges. In the power range up to 100 MW_{Fuel}, which can be interesting for the thermal utilization of biomass, there are less technical constraints for fluidized-bed technology. However, these technologies are usually downwards restricted with respect to power load due to systems engineering and economical aspects.

2.3 Gasification in fixed-bed reactors

In fixed-bed reactors there is a fuel bulk filling in the reaction chamber. Fresh biomass is fed from the top of the reactor, introduced through an opening or sluice on the reactor head and sinks slowly downwards by gravity as conversion of fuel conversion proceeds. A characterization of the various manners of operation of fixed-bed reactors results through the relative direction of gas stream and fuel bed movement (up- and downdraft).

2.3.1 Fixed-bed updraft gasifier

With updraft gasification the gasification medium and the produced wood gas flow through the gasification reactor in the opposite direction to the fuel bed. Thus if the reactor is fed from above, the gasification media (air, oxygen, steam) enters the reactor in the area of the grate. With this method of gasification clearly defined reaction zones arise in the bulk filling. The sensitive heat of the produced raw gas is used to dry the fuel and to start pyrolysis. In this manner, the raw gas is cooled strongly on its way through the bulk filling.

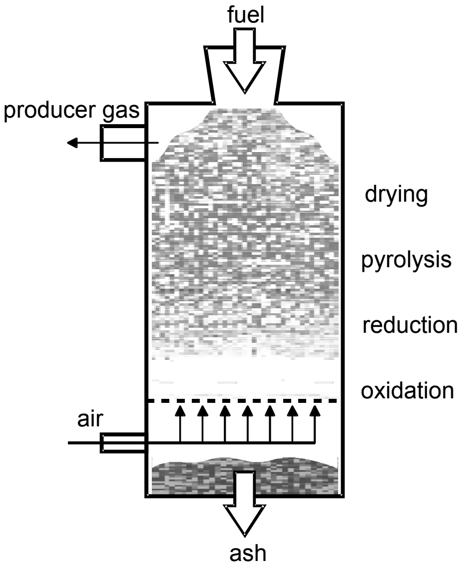


Figure 2-4: Schematic diagram of an updraft gasifier

As can be seen in the schematic diagram in Figure 2-4, the products of decomposition released in the pyrolysis zone and the steam released as a result of fuel drying are discharged directly out of the reactor with the producer gas. The problematical pyrolysis gases are not conducted through any hot zone and can therefore not be suitably split up or oxidized. The tar content in the raw gas can thus reach values over 100 g/m_n^3 during gasification of the biomass. The direct discharge of pyrolysis vapors out of the reactor can be shown be the effect, that with this type operation mode mainly primary tars can be found in the producer gases [4] from updraft biomass gasification plants. In comparison to updraft gasifiers the downdraft or double-

fire gasification process possess a producer gas contamination with less condensable producer gas contaminations.
Fundamental fuel requirements for the gasification of biomass are presented in Table 2-1.

Table 2-1: Requirements for fuel quality with updraft gasification [4]

Water content	< 40 $\%_{\text{Mass,wet}}$
Grain size	0.5 – 20 cm
Share of fine particles	< 30 $\%_{\text{Mass,wet}}$ (≤ 5mm)
Ash content	< 6 $\%_{\text{Mass,dry}}$

The steam accumulating in the drying zone is, like the pyrolysis vapours, drawn off directly with the stream of producer gas. The sensitivity of updraft gasification to fuels with high water content is low. Since the fuel enters the oxidation zone in dried form, in updraft gasification steam is added in many cases to the gasification air. Through the reaction of the steam with the glowing charcoal (endothermic water gas reaction) in the oxidation zone, the fuel bed is cooled. The ash melting point is usually not exceeded and slagging problems can therefore be prevented.

2.3.2 Fixed-bed downdraft gasifiers

With downdraft gasification the gasification medium flows through the gasification reactor in the direction of the sinking bulk filling. The drying/pyrolysis zone lies above the oxidation zone and is supplied with the necessary process heat primarily through thermal conduction in the bulk filling. In the oxidation zone primarily vaporous pyrolysis products react with the input gasification medium. The gases (CO_2 und H_2O) leaking from the oxidation zone are reduced to CO und H_2 by the glowing charcoal of the lower lying reduction zone. Through these reactions, the endothermic Boudouard- and the water gas reactions, a portion of the sensitive heat of the smoke gases is converted again into chemical energy of the producer gas. Here the gas temperatures sink to a level at which no further reaction of the charcoal with the producer gas takes place. Consequently, there is always a layer of unreacted charcoal above the ash grate that has to be discharged with the ash. As a result, with this type of gasification one can always reckon with an increased portion of charcoal residue in the ash. Under optimal operating conditions it is possible to attain fuel conversion (= combustion) rates of over 95$\%_{\text{Mass, dry}}$ [4] The producer gas is removed from the reactor close to the ash grate.
The consequence of this type of process control is that products originating in the pyrolysis zone have to pass through the oxidation zone, which is denoted as the “hot treatment zone for tarry compounds”, and become there transformed to a great extent into stable gases. This leads as a rule to considerably smaller concentrations of tar compounds in the producer gas than with downdraft gasification. An approximate value according to [9] is a load of 1 g/m_n^3. The organic compounds that are still contained in the producer gas after conversion of the pyrolysis vapours in the hot oxidation zone at 1000°C to 1200 °C are classified in [9] as tertiary tar compounds. These processes can be operated with cold gas efficiencies between 60% to 80%.

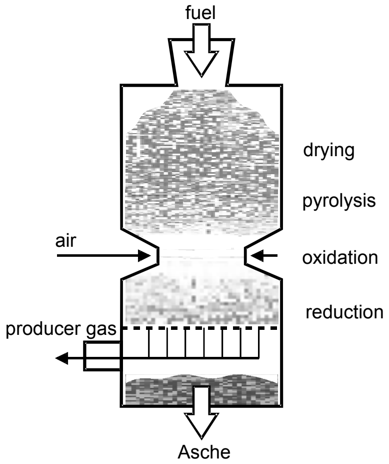


Figure 2-5: Schematic diagram of a downdraft gasifier [4]

When the gasification medium is fed in via radially arranged jets, the problem is to ensure a sufficient depth of penetration of the medium into the fuel bed. In the event that the formation of the oxidation zone is not uniform over the entire cross-section, the danger exists that pyrolysis vapours are discharged along with the producer gas. The additional feeding of the medium through a central pipe can help to bring about a uniform distribution of the hot areas over the entire reactor cross-section. The problem of ensuring uniform reaction conditions from a certain reactor size upwards is responsible for the limited possibilities of upscaling downdraft gasifiers. In this regard, [5] indicates a fuel thermal output of 1 MW_{th} as the recommended value for the upper limit of sensible upscaling of individual gasification reactors. Investigations [10] have shown that in the case of up-scaling a downdraft gasifier by a factor of 2 the quality of the air supply, due to bad bulk penetration with partial oxidation media, can sink by about 50%, which leads to a corresponding worsening of the producer gas quality.

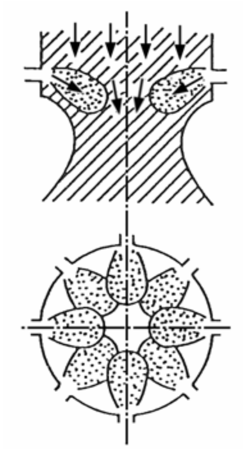


Figure 2-6: Formation of the oxidation zones upstream from the air inlet openings of a downdraft gasifier [4]

The construction- and process engineering principle of downdraft gasifiers makes them sensitive to the quality of the fuel that is used. Particular attention must be paid primarily to the water content of the fuel. The entire steam liberated in the drying zone must be removed through the bulk filling; i.e. besides the evaporation heat that has to be produced, the vapour must be heated up to the temperatures in the oxidation zone. As well, heat is withdrawn from the oxidation zone through the endothermic water gas reactions, i.e. the conversion of the steam through a chemical reaction with the glowing charcoal. As a result, with high amounts of water in the fuel it is not possible to ensure the high temperatures in the oxidation zone that are important for the conversion of the pyrolysis vapour. Adequate conversion of the pyrolysis products is then possibly no longer guaranteed. With regard to the grain size, fine- and ash portions of the fuel, these fuel parameters can strongly influence the uniformity of the flow through the fuel bed through increased pressure loss, channel formation, slagging, etc. It is therefore necessary to take the basic data about fuel quality in downdraft gasification presented in Table 2-2 into consideration.

Table 2-2: Requirements for fuel quality with downdraft gasification

Water content	10 - 25 $\%_{\text{Mass, dry}}$
Grain size	2 – 20 cm
Share of fine wood particles	< 15 $\%_{\text{Mass, wet}}$ (≤ 5mm)
Ash content	< 6 $\%_{\text{Mass, dry}}$

When applying this process technology there are numerous constructional variants that in part strongly deviate from the schematic diagram presented in Figure 2-6 of a classic downdraft gasifier with air supply near the throat section, the “cooker”, of the combustion chamber (gasifier according to the Imbert principle [11]). Moreover, downdraft reactors (“stratified downdraft gasifier” or “open top reactor”) are presently being constructed whose combustion chamber is designed cylindrically over the entire height without tapering. The gasification medium and the fuel are fed together through the open upper section of the reactor. This method evidently guarantees an uniform distribution of the gasification medium over the entire reactor cross-section and thus a homogeneously formed oxidation zone and reliable conversion of the pyrolysis vapours.

2.3.3 The double fire gasifier

Gasification in a double fire gasifier represents a combination of downdraft and updraft gasification. In the upper part of the gasifier the fuel is converted by means of a downdraft. From the details on downdraft gasification given above it is clear that a certain amount of unreacted charcoal accumulates in the reduction zone. The purpose of two-zone gasification is to use updraft gasification to convert this residual fuel in the grate area completely into producer gas. This principle is presented in Figure 2-7.The design of the reaction areas in the upper section corresponds to downdraft gasification; in the area of the ash grate there is an additional second oxidation zone. Extraction of the producer gas from the reactor is via a collecting duct located in the area of the reduction zone.

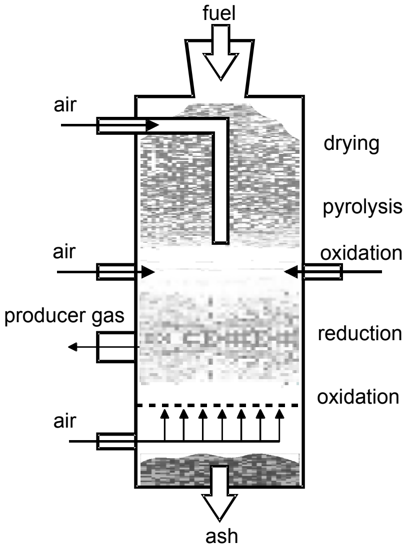


Figure 2-7: Schematic diagram – Two-zone or double fire gasifier [4]

Advantages of this process are the complete conversion of the fuel into producer gas and the possibility – with suitable location of the collecting duct - of having the crude gas produced in descending gasification go through a further hot zone. This may facilitate a conversion of pyrolysis vapors that are still present. These advantages over downdraft gasification, but especially over updraft gasification, are gotten at the price of a considerably higher gas exit temperature.

The demands made by two-zone gasification on fuel quality correspond to the criteria of downdraft gasification as shown in

Table 2-2, since the greatest amount of the fuel is converted in the initial oxidation zone primarily when biomass is used. There are presently no generally accepted recommended values for the expected loading of the raw gas with tar. With this type of process operation the tar loading in the raw gas lead maximally to a range of loading of downdraft gasification. Due to the second oxidation zone in the area of the raw gas exit, with suitable geometrical construction much lower tar concentrations can be expected [12].

2.3.4 Staged fixed-bed gasification systems

Staged systems for biomass gasification are based on the separation of the partial processes of thermo-chemical conversion (drying, pyrolysis, oxidation, reduction) in reactors separated from one another. The separation of the process steps permits a greater influence on the partial steps, which results in higher concentrations as well as very little load in the form of condensable hydrocarbon compounds (tar loads). As a result, detrimental effects are greatly improved in shaft gasification systems that are in connection with not clearly separated zones in the process steps of thermo-chemical conversion of the shaft gasifier (e.g. downdraft gasifier or updraft gasifier).

Residual drying and pyrolysis of the biomass take place in the first step. Depending on the process step and interconnection variant it is possible to serialize several pyrolysis steps. At the end of the pyrolysis step one gets separate fractions of pyrolysis coke and pyrolysis gas.

The pyrolysis gas, which is loaded to a high degree with organic tarry compounds, is partially oxidized in a combustion chamber (in which temperature, turbulence and retention time can be adjusted) to bring about a chemical reaction and conversion of the tarry compounds. The oxidation within the step of partial combustion is usually realized at the freeboard above the char fixed bed (DTU, TKE), or is conduction in external combustion chamber (TUG), from where the hot of off gas is routed into the chamber, where reduction reaction take place.

The resultant amounts of energy set free serve to maintain the endothermic reduction of the pyrolysis coke, which reduces the pyrolysis- and (charcoal) coke with the combustion gases from partial oxidation to the stream of producer gas. The carrying along of volatilizable pyrolysis products (tar-loaded pyrolysis gas, chemically bonded tar compounds of low-temperature pyrolysis coke, etc.), which can still be present as a result of the influence of temperature in the reduction zone and due to an existing residual degassing potential and non-developed temperature zones, is hindered because of the better regulatability of residual drying, pyrolysis and partial oxidation of the infed biomass and intermediate pyrolysis products – such carried along pyrolysis products can no longer be brought to conversion in the reduction zone and thus lead directly to the emission of tarry compounds in the raw producer gas.

The development of staged gasification system in the recent past have shown different concepts, which are based on a consequent separation of reaction and conversion zone for drying and pyrolysis, partial oxidation and reduction. The main difference between these concepts can be found in the procedural design of the apparatuses and the technical solution for flux of external into the process as well as design of partial oxidation zones.

The following figures show different examples of stage concepts for the gasification of biomass. Figure 2-8 shows the Viking gasifier of the Technical University of Denmark (DTU) [13-15], which is also known as the two-stage gasifier. The process is characterised by two separated reactors: The first is an indirectly heated screw feeder, in which pyrolysis is realised, the second zone is a combined reactor for partial oxidation of pyrolysis gas (main tar conversion) and for the heterogeneous gas-char reaction (reduction/gasification process). The main advantage of these concepts is a producer gas contamination with tarry compounds below 25 mg/Nm³, which allows falling below the gas engine limiting values for the producer gas utilisation with out any secondary gas treatment and gas cleaning. The low producer gas content results from the catalytic properties of the char bed.

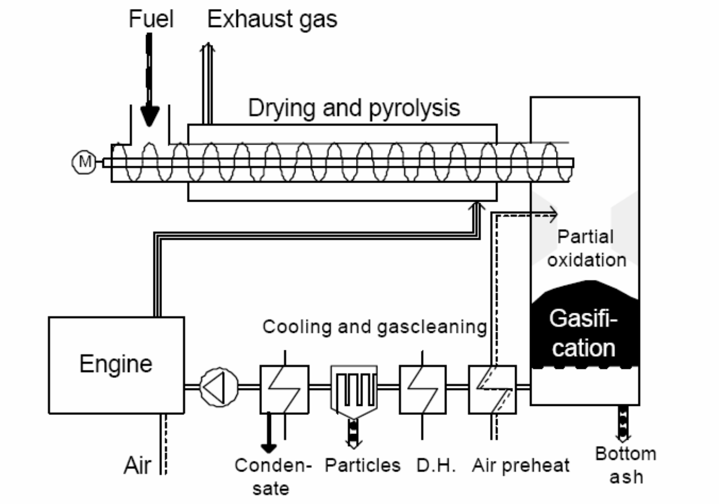


Figure 2-8: Two-stage “Viking” gasifier of the Technical University of Denmark, DTU [13-15]

Figure 2-9 illustrates the 3-stage gasifier of Thomas Koch Energi (TKE, Denmark). In contrast to others, no external heat is used for the pyrolysis step in this staging concept. Pyrolysis is carried out by partial oxidation of the solid fuel.

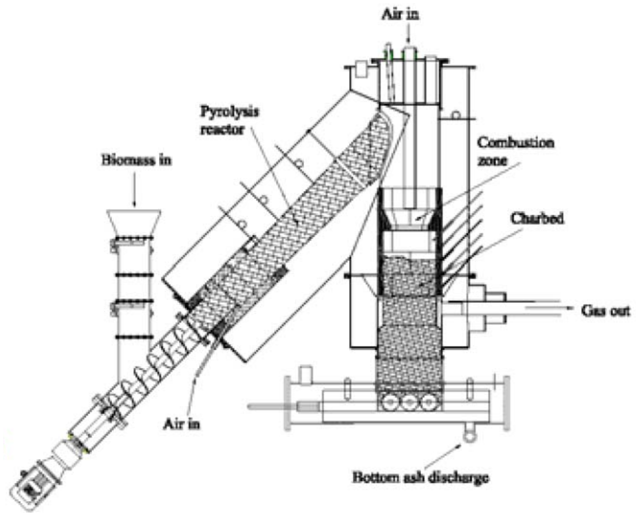


Figure 2-9: TK Energy „3-staged gasifier“ 400kW$_{th}$ [16]

Figure 2-10 shows the staging principle of the CleanStGas Concept (**Clean-St**aged**Gas**ification) developed at Graz University of Technology in Cooperation with partners from industry. It is characterised by a consequent design of the different reactors, where the thermochemical conversion steps of pyrolysis, partial oxidation and reduction can take place.
All three staging concepts evolve in a low-tar producer gas below the limits of IC engines. Hence, no tar precipitation in a wet gas cleaning and consequently no waste water treatment are needed, which brings well-known benefits for plant economics in the lower and middle range of power.

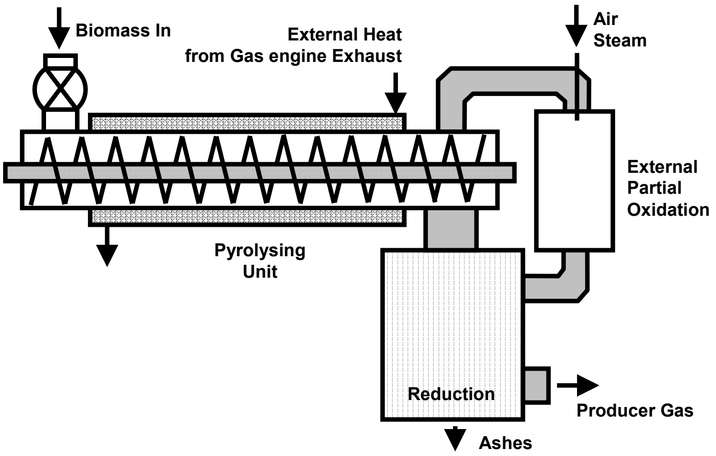


Figure 2-10: CleanstGas Gasifier Graz University of Technology, TUG [17, 18]

It is also known, that staged gasification with heat reflux from the process chain into pyrolysis (with engine exhaust or producer gas) results in higher cold gas efficiencies compared to single-stage (shaft) fixed-bed gasifiers, since less air is needed for the thermal conversion of the fuel.

3 Fundamental description of the process steps

Chapter 3 provides a survey of the process chain of biomass gasification technology in the individual process steps. A schematic overview of processes can be seen in Figure 1-1. A short description of the individual process steps and modes of operation in these steps, as well as a number of important points that must be taken into consideration on the basis of the present state of knowledge, are presented in the following. A detailed description and the differentiation of the various processes for realization of the entire process chain are provided in sub-chapters 2 to 7.

A listing of important points can be found in the following sub-chapters; non-observance of these points may entail negative effects on the normal operation of the plant and possible hazardous situations. Such situations and their control are not treated in the subsequent chapters. Furthermore give the overall technology fundamental basics for hazards identification and risk assessment provided in a draft guidlinie and concluding finale guideline “Gasificaiton Guide – Safe and ecofriendly biomass gasification”.

It must be emphasized at the beginning of such a detailed description of the individual process steps that in biomass gasification facilities an explosive mixture of toxic and combustible gases, and amounts of residual substances in combination with gas production and gas cleaning are produced, extracted, converted and recycled that may act upon the human organism to damage health (poisoning, danger of suffocation, danger of fire and explosion) as well as upon the environment (plant emissions as a result of producer gas pollutants and gas cleaning residues). For this reason and to protect human health and the environment, suitable requirements must be set regarding the technical equipment of such facilities.

Completeness of the information and data provided in the given cases and examples is excluded. Other cases and examples are feasible.

3.1 Fuel, fuel storage, transport and feeding

Fuel storage, transport and feeding have an important influence on the quality of the fuel itself (e.g. due to drying processes during storage), as well as the process stability (e.g. producer gas quality, stability of heat and power production, etc.). In addition, the emissions expected in this area (delivery times, delivery intervals, noise and dust emissions during the (re)filling of the storage depot, vapours from the drying process) and the applicable fire and dust explosion protection regulations should also be considered.

With regard to the nature of the fuel it must be kept in mind that this project assumes the use of unprocessed (forest) natural wood chips, as possibly standardized in [2], [3] of a grain size suiting the requirements of the gasification system.

For the area of fuel storage, transport and feeding it can also be noted that the possibility of the generation of a dust explosion exists with wood chips with a high fraction of fine wood particles or wood dust. For these plant areas the plant operator is obliged to comply with explosion protection measures as stipulated by ATEX (cleanliness, avoidance of dust raising, combined fire/ignition protection, selection of wood chip production process etc.).

3.2 Storage of fuel and auxiliary fuel

Fuel storage includes the area of fuel delivery and treatment of the fuel during the storage period. The stored amount of fuel is dependent on the respective configuration of the plant (performance range, fuel logistics, and plant operating state). Besides the amounts of biomass fuel it is also necessary to pay attention to the storage of auxiliary fuels (propane gas, diesel fuels, etc.) for various co-combustion purposes as well as combustible operational supplements (lubricating oils, washing emulsions for the operation of the gas cleaning plant, etc.) and residues from plant operation. Beside different auxiliary fuels for plant operation different plant utilities are needed, which ensure the stable plant operation. Plant utilities like nitrogen, pressurized air, water, steam, air supply, etc. has be provided in sufficient amounts, as required to be able to operate the plant on stable load of power.

Important points that have to be considered:

- inspection of the quality of the fuel upon delivery
- delivery logistics (delivery times and frequency regarding possible unacceptable annoyances of adjoining residents, noise and dust emissions during delivery)
- the drying process during the storage period (drying air is passed through the bulk filling, turning of the filling, fuel turnover)
- energy requirement for drying (natural vs. forced drying), [combined with the release of dust and moisture]
- fulfilment of general technical requirements regarding the construction of storage depots/storerooms/storage sites (fire protection, regional development, structural engineering…)
- components - fire protection [21]
- temperature monitoring in the fuel storage room [21]
- fire-extinguishing system (sprinkler system) (Note: Regulations on the construction of the fire protection system must be coordinated with the pertinent fire-protection expert of the licensing public authority).
- inspection of the fuel quality before/during the transport of the fuel out of the storeroom
- health hazard (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.3 Fuel conveyance

Fuel conveyance entails transport of the fuel from the fuel depot to the fuel feeding system (e.g. the dosing unit and contaminants removal system of the gas generator (gasifier) in sufficient volume and quality (possible integrated: sieving, removal of contaminants and foreign material, drying unit, etc.). Depending on the grain size of the fuel and the storage conditions (area, storage height) various discharge systems can be considered for the transport of the fuel from the depot:

- travelling grate
- walking floor

Important points that have to be considered:

- easy to operate and maintain
- constructive design [stability, reaction to foreign matter]
- fire protection [21] and explosion protection
- construction of the fuel transfer points as a fire lobby boundary (susceptibility to faults, dust raising, danger when servicing, troubleshooting during operation …)
- fire-extinguishing system (sprinkler system) (Note: Regulations on the construction of the fire protection system must be coordinated with the pertinent fire-protection expert of the licensing public authority)
- additional fire protection precautions and devices that are necessary due to special requirements in plants with integrated biomass drying [21]
- health hazard (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.4 Feeding fuel into the reactor

Feeding fuel into the gas generating reactor is normally by means of clocked conveyance systems activated by the output regulation of the entire system. Fuel feeding has to be carried out via a gas-tight transfer canal that prevents gas leakage and the aspiration of excessive amounts of leakage air. Depending on the grain size of the fuel to be transported, the following transport systems are used:

- belt conveyor
- chain conveyor or trough chain conveyor, respectively
- screw conveyor
- vibrating conveyor for dosing into the transfer system
- stop valve transfer system
- squeeze valve system
- rotary valve system
- double sluice system

Important points that have to be considered:

- leak tightness of the transfer system between conveyor system and reactor
- backfiring stop (firebrands, low-speed deflagration, etc.)
- anti-backfiring system (valve-, rotary valve system) [21]
- self-activating fire-extinguishing system (sprinkler system) in the event of backfiring
- dosing into the feeding system depending on the function (valve-, cylinder-, rotary valve system)
- technical construction of fuel-conveying components with regard to susceptibility to faults due to blocking (due to fuel compression, overly large misshapen fuel particles or foreign matter)
- gas leakage during a breakdown (e.g. selective extraction-/aeration system close to the fuel dosing/fuel transfer systems in the event of gas leakage during breakdowns during the recurrent feeding operation)
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.5 Gasification reactor

The thermo-chemical conversion of solid biomass into raw producer gas takes place in the gasification reactor (gasifier). The biomass generally goes through the conversion steps of drying, pyrolysis, partial oxidation and reduction, which converts the input mass flow of solid biomass into an output mass flow of producer gas with desired products: permanent gas (H_2, CO, C_xH_y, CO_2, N_2), undesired products: particulate matter, dust, soot, inorganic pollutants and organic pollutants (tars) as well as ash. Depending on the gasification principles (reactor geometry, used gasification agents – air, steam, oxygen) different qualities of the producer gas relating gas composition, tar content, dust content in the raw gas before gas cleaning can be achieved.

Important points that have to be considered:

- gastight fuel feeding system regarding positive and negative pressure
- reliable performance of the filling level monitoring device
- reactor geometry and inner reactor surface structuring, which promotes the gradual sinking of the fuel filling and prevents the formation of dead space.
- homogeneous, stable reaction conditions in the respective reaction zones
- sufficient retention times in the reaction zones
- controlled air supply in the individual reaction zones
- temperature and environmental stability (reduced conditions) of the reactor body (reactor shell, brick lining and hot gas components)
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.6 Gas cooling

The purpose of gas cooling is to lower the producer gas temperature to fulfil the requirements and necessary producer gas temperatures due to the optimal operation conditions of the present gas treatment step. In demonstration facilities the reactor discharge (500-800°C) is cooled down to a level of about 600-100 °C, e.g. to be able to carry out dry particle filtration with ceramic filters or fabric filters respectively.
For gas utilization a temperature range of below 40°C is required to attain a volumetric efficiency in the gas engine that is as high as possible – therefore adequate cooler and chillers have to be installed, which allows to decrease the producer gas temperature on a certain stable level as well as which allows to fall below the dew point of the producer gas (remind: Condensation of tarry compounds and water vapour together with dust have to be kept in mind). The lower limit of the temperature range is restricted by the temperature level of the heat sink, which means that there are certain limitations from return line temperatures of the district heating system or ambient temperatures, when aiming at auxiliary cooling system to open air. Heat sink to open air is principally possible, but not desirable with respect to an efficient utilization of biomass and has to be matched with corresponding guidelines on the sufficient energy budgeting and sustainable usage of energy. The gas cooling therefore requires well founded design of the various heat exchangers according to the application requirements of wood gas and its efficient usage in IC engines.

Important points that have to be considered:

- the usable heat, as far as possible, must be usefully extracted and not “destroyed” through quench devices at the lowest level (see also total efficiency)
- the conditions for gas cooling are defined by the inflowing producer gas and the requirements of downstream gas cleaning.
- selection of a suitable type of heat exchanger
- additional devices related to the process for support of start-up and shutdown operation (pre-heating, fouling, …)
- observance of the specific special gas requirement (ash- and dust loading, tar loading…) with regard to providing for regeneration facilities and erosive properties of the producer gas
- pressure losses in the heat exchanger on the producer gas side
- maintaining the temperature level through temperature-controlled process regulation in the respective plant system components – prevention of blocking of gas-conveying pipes/assembly groups due to condensation of tarry components
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.7 Gas cleaning

Gas cleaning fulfils the purpose of providing constant gas qualities for gas modules independent of fluctuating producer gas contamination due to discontinuous processes in the gas generator (gasifier) and in fuel feeding, which leads to fluctuations in the quality of the raw gas. Gas cleaning has the task of de-dusting the producer gas as well as ensuring suitable purity regarding tar load. Here two ways are possible: firstly, combined gas de-dusting and gas cleaning by means of suitable scrubber columns or, secondly, separate gas de-dusting and gas cleaning by means of a preliminary hot/warm filtration for particle separation with subsequent gas cleaning of tarry compounds, whereby attention must be paid to the subsequently required costs for separation of mixtures and for processing and disposal, e.g. waste water treatment.

Important points that have to be considered:

- toxicity of the cleaned materials and the materials separated from the raw producer gas
- implementation of processes and apparatus for the treatment/management of process media (gaseous, liquid, solid)
- monitoring of the clean gas quality of the product
- producer gas side pressure loss / applying the necessary pressure difference to convey the gas to the engine by means of a gas blower
- energy requirement of gas cleaning (total fuel efficiency of the plant)
- processing of the producer gas to guarantee minimum parameters for gas engine use (as an example, Table 3-1 compares the raw gas values [particle and tar content] of a downdraft gasifier with the demands made on the gas aspirated by the gas engine – it becomes apparent what gas cleaning in combination with gas cooling has to perform.)
- treatment of the waste products from gas cleaning
- measurement of operation parameters of the respective technology concept
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

Table 3-1: Particle and tar loading of the wood gas with a good downdraft gasifier in comparison to requirements when using the gas as fuel in an engine [22]

	Raw gas values (optimised downdraft gasifier) mg / m^3_n	Clean gas requirements for engine applications mg / m^3_n
Particle	100 – 1,000	At least < 50 If possible < 5
Tar	100 - 500	At least < 50 If possible < 25

3.7.1 Dry gas cleaning

The purpose of dry gas cleaning is the removal of particulate matter from producer gas to reduce problems in the sub-sequent steps of the remaining process chain (e.g. gas cooling or utilization). Dry gas cleaning can be divided into hot gas cleaning with heat-resisting filters (at raw gas temperatures typically above 500°C and before gas cooling) and into dry gas cleaning in fabric filters (typically below 200°C after gas cooling).

Filter elements for hot gas cleaning typically consist of porous ceramic or sinter metallic materials. Hot gas cleaning is primarily interesting for gas utilization at high temperatures (gas turbines and fuel cells). Secondarily, it can be interesting to lower the particle load in the heat exchangers during gas cooling.

Tar condensation is prevented by maintaining a minimum producer gas temperature; by adding adsorbents it is also possible to reduce the tar content in certain temperature and concentration ranges. Excessive tar condensation would result in operational malfunctions because the regeneration of the surface of the filter system and the apparatuses would no longer be possible.

Possible cleaning steps in the hot gas cleaning process can be the following:

- cyclone - primary de-dusting (prior to gas cooling)
- hot gas filter - fine de-dusting (prior to gas cooling)
- bag filter system - fine de-dusting (after gas cooling)
- other filters (sand bed filter, active coke bed)

Important points that have to be considered:

- thermally highly stressed components close to the hot primary de-dusting process prior to gas cooling
- temperature control in the dust filter (too high temperature: damage to filter units; insufficient temperature: tar condensation)
- selection of the regeneration device and regeneration agents
- auxiliary power requirement for auxiliary heating devices and blowers for conveyance of the producer gas
- removal and recycling of the gas cleaning agents (soot, ash, dust etc.)
- drawing up of operating and maintenance instructions for the gas cleaning system
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.7.2 Wet gas cleaning

Wet gas cleaning is purification of the producer gas by means of liquid scrubbing agents in a suitable scrubber system. The cleaning effect is brought about by the adherence of the contaminants to and the dissolving of the contaminants by washing agents. This kind of gas cleaning additionally fulfils the function of gas cooling because of the heat exchange between the producer gas and the washing agent due to

the intensive contact and the heat removal through heat extraction via suitable heat exchangers. Washing agents used are water, water/oil (e.g. biodiesel RME) emulsions, condensate and various hydrocarbons.
After wet gas cleaning the producer gas can be used for combined production of heat and power, e.g. on basis of gas engines, gas turbines or fuel cells as the conversion unit. Guidelines and recommendations exist for gas utilisation in gas-burning modules or gas burners, which refer to natural gas application, analogues to be applied - explicated guidelines for wood gas use in gas burning units are not available so far.

Important points that have to be considered:

- chemical resistance of the used materials to the various agents (condensates, hydrocarbon compounds, alcohol compounds, alkaline and/or acidic producer gas components and regulatory chemicals)
- processing, transport, if applicable storage, if applicable disposal of accumulating gas cleaning waste.
- temperature monitoring of the washing agents
- temperature and pressure monitoring of the producer gas
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.8 Gas utilization

3.8.1 CHP plants (gas engine)

Plants, in which power and heat are generated together, are generally referred as cogeneration plants. If this technology is used for the low and medium power output range in compact plants, the technology is called combined heat and power plant (CHP plant). Individual modules of the current type function in an output range of maximally 2 to 3 MW_{el}. In this document the processes of power conversion/combustion inside the engine are not treated – however, all system components involving the CHP plant as well as mass input and output are incorporated in the following description.

3.8.1.1 Gas conditioning and gas transfer to the gas engine

The stipulations of the respective CHP plant manufacturer are to be complied for the plant section involving gas utilisation; in turn, manufacturers makes specific demands on conditioning and transfer of the gas. The gas conditions step within biomass gasification plant concepts have to fulfil the function of a final processing of the producer gas to guarantee nearly constant producer gas temperature, heating value, humidity as well as a certain gas engine inlet pressure to prevent gas engine malfunctions due to exceeding or falling below of required producer gas property values.
Table 3-2 provides an overview of a well-known manufacturer of special gas engines for prescribed producer gas conditions, which are listed as examples. The operation of such modules in the event of deviations and exceeding of the required producer

gas quality values must be coordinated with the respective manufacturer with regard to warranty and guarantee aspects.

Important points that have to be considered:

- efficient gas cooling upstream from the engine (filling level of the cylinder) [in combination with gas cleaning and cooling]
- gas pressure regulation upstream from the engine
- gas/air mixing system
- mixture-supercharging with or without intercooler
- gas safety regulations for operation and maintenance
- safety precautions against a condensate failure in the gas mixing system
- demands made on the composition of the producer gas by the engine manufacturer (temperature, thermal value and pressure) as listed in Table 3-2 (In individual cases, however, the demands made on the purity of the producer gas must be cleared with the engine manufacturer)
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

Table 3-2: Exemplary requirements for the producer gas of GE Jenbacher and Klöckner-Humbold-Deutz engines to comply with warranty conditions [23], [24]

GE Jenbacher			**Klöckner-Humbold-Deutz**	
	Without catalytic converter	With catalytic converter		
Max. temperature (°C)	40	40	Max. temperature [°C]	10< t <50
Max. rel. moisture (%)	80	80	Max. rel. moisture (%)	<80
Condensate	0	0	Condensate	0
Max. grain size (µm)	3	3	Grain size [µm]	3-10
Dust max. amount (mg/kWh)	5	5	Dust content [mg/m^3_N CH_4]	< 10
Max. content of sulphurous compounds reckoned as H_2S (mg/kWh)	200	115	Sulphur content total S [mg/m^3_N CH_4] H_2S content [%$_V$/m^3_N CH_4]	2200 0.15
Max. total halogen content (sum Cl + 2x sum F (mg/kWh))			Chlorine content total Cl [mg/m^3_N CH_4]	<100
Without restriction of warranty	< 10	0	Fluorine content total F [mg/m^3_N CH_4]	<50
With restricted warranty	10-40	0	Sum of chlorine + fluorine [mg/m^3_N CH_4]	<100
No warranty for damage attributed to increased halogen consumption	> 40	0	Ammonia NH_3 [mg/m^3_N CH_4]	<30
Max. silicon content (mg/kWh)			Net calorific value [kWh/m^3_N] Change rate [%/min]	≥4 <5
Without restriction of warranty	< 2	0	Oil vapours (> C5 < C10) [mg/m^3_N CH_4]	<3000
With restricted warranty	> 2	0	Oil vapours (> C10) [mg/m^3_N CH_4]	<250
Max. ammonia content (mg/kWh)	5.5	5.5	Silicon organic [mg/m^3_N CH_4]	<10
Max. residual oil content in the Fuel gas (mg/kWh)	0.5	0.5	Gas pressure fluctuations [mbar] Fluctuation frequency < 10/h	20 +/- 10

The limit values listed in the table above refer to current long-term tests and experience gained from the development of catalytic converters. The targeted zero values referred to are justified by the fact that these components can be regarded as absolute poisons for catalytic converters and must therefore be avoided - no data has been presented regarding verification methods and limits. This technology is in the process of development to be ready for marketing - the testing of various catalytic converters and the exact prerequisites for their permanent use will spur manufacturers in future to develop suitable ideas about limiting values. The limit values for the product used must be agreed upon in detail through consultation with the manufacturers.

3.8.1.2 Secondary treatment of exhaust gas

The following components can be expected in engine exhaust gas:

- carbon dioxide ($CO_{2)}$
- oxygen (O_2)
- carbon monoxide (CO)
- organic hydrocarbons (C_xH_y)
- nitrogen oxides (NO_x)
- nitrogen (N_2)
- steam (H_2O)
- trace elements of organic and inorganic substances

Products from incomplete combustion or from producer gas slip (predominantly CO and C_xH_y) and high-temperature or fuel-nitrogen combustion (NO_x) necessitate the operation of secondary treatment systems with regard to stipulated emission limits insofar as engine-specific measures are insufficient for minimizing pollutants in the engine gas. Treatments with various techniques involving catalytic converters or post-combustion techniques, which guarantee compliance with emission limits, are principally possible. Long-term experience regarding the effectiveness and service life of catalytic converters is presently not yet available. Service life is influenced substantially by catalyst poisons, e.g. heavy metal compounds, alkali compounds, etc., which in part reduce the activity of the catalytic coating very quickly.

Important points that have to be considered:

- safe, reliable evacuation of exhaust gas
- maintaining pertinent plant components
- complying with recurrent plant maintenance intervals
- observing the sound problem
- observing the emissions problem
- safety measures against hot surfaces in the area of secondary treatment of exhaust gas
- complying with exhaust gas emission limit values
- health hazards (danger of suffocation, contamination with residues and condensates)

- danger of fire and explosion (engine control system with suitable control of load shedding and emergency stop functions).

3.8.1.3 Heat usage from CHP plants

The thermal energy from the CHP plant (exhaust gas, internal cooling processes etc.) can be used for the energy supply of district heating systems. In addition to the recovery of heat energy from the engine exhaust gas, heat energy is available from engine block cooling; this, together with the recovered exhaust gas heat as well as process heat from producer gas cooling, can be fed into a local district heating systems. Potential process-internal heat for drying of biomass, waste water processing, staged gasification, etc., can be extracted from these available amounts of heat.
A biomass gasification facility must be classified as a base load plant in a local heating network because it has higher plant-specific costs due to the generation of combined heat and power. For economical operation, therefore, the goal is to have as many full load hours as possible, thus ensuring continuous power generation throughout the year. With regard to the number of full load hours particular attention must be paid to the dimensioning/classification of the cogeneration plant so that over the annual period of the energy requirement of the local heating network the purchase of the produced amounts of heat by the local heating network is ensured.

Important points that have to be considered:

- adaptation of the plant size (i.e. power range) as a base load plant to the local heating network – heat-controlled operation!
- coverage of middle and peak load by means of suitable heat generators
- coverage of the heat requirement in the event of a system shutdown or a system failure due to a fault.
- heat removal for an outage in the supply of heat locally
- control facilities to maintain the return temperatures of the local heating network so as to maintain maximally permissible engine cooling circuit inlet temperatures
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

3.8.2 Auxiliary- and emergency gas recycling facilities

In general, gas engine-CHP plants are designed for the utilization of the producer gas. However, there are examples of plants in which the producer gas is used in boiler systems to generate additional process heat. In the event of a failure of these plant systems, as well as a failure of the CHP plant, an emergency flare must be kept in readiness in any case for the producer gas to be able to dispose of (burn) arising amounts of gas in a controlled manner.
The plant operation requires the supply of various auxiliary product streams to the plant, which includes water, nitrogen, pressurized air, auxiliary fuel (natural gas, liq-

uefied petroleum gas, light fuel oil), electricity (infeed and consumption), heat infeed systems to local district heating as well as auxiliary cooling devices, disposal tanks and containers etc. The supply chain has to be controlled by the process automation that malfunctions due to failure of auxiliary media and energy can be prevented.

Important points that have to be considered:

- suitability of the gas devices in use for use with special gases
- suitable load and throughput regulation for the entire plant in the case of multiple gas use
- flame- and/or temperature monitoring in the gas modules and in the flares
- availability of auxiliary firing (selection of flare geometry and auxiliary fuel; suitable pre-mix of the combustion gas (producer gas and atmospheric oxygen)
- start procedure for the emergency gas flare (igniting the flare or a flare with a permanent standby flame
- contingency procedure for the failure of the producer gas emergency flare (pollution, auxiliary firing failure)
- health hazards (danger of suffocation, contamination with residues and condensates)
- Adequate design and construction of auxiliary units for the supplying auxiliary plant media und energy streams.
- danger of fire and explosion

3.9 Accumulating residues and aspects relevant to health

In the operation of biomass gasification plants different residues from gas production (gasifier), gas cooling and gas cleaning as well as gas conditioning can accrue. Such residues have to be treated for suitable processing (residues treatment and/or partly refeed to gasifier or biomass combustion boilers) and, if applicable, put to disposal. Such residues are listed in the following:

- ash
- dust particles
- condensates (with/without organic and inorganic load)
- sludge from gas cleaning
- waste water from gas cleaning
- water-oil phases out
- other residues from cleaning and maintenance

Accumulating residues contain primarily constituents that correspond to those of the producer gas. However, in most cases these residues indicate these constituents in higher concentrations on account of the accumulation of producer gas contaminants (e.g. waste water, washing agents), which requires special precautionary measures aimed at properties that endanger health and the environment. With regard to the properties of the residual materials (and also producer gas components) that are relevant to health, attention is drawn to the substances given in Table 3-3:

Determination of the single concentrations is by means of chemical laboratory verification methods, the aid of substance decomposition, measurement of electrochemical properties, gravimetric verification methods, etc. that allow the obtainment of necessary plant residues properties, which are required within permission procedure. The measuring methods deliver variables that in turn deliver quality parameters for arising plant waste and, depending on the value of the variables, stipulate special waste treatment-, recycling- and waste handling measures.

- Phenol index
- Chemical oxygen demand - COD
- Biological oxygen demand - BOD
- Total Organic Carbon – TOC
- Measurement methods with gas and liquid chromatography

Table 3-3: Listing of possible gaseous emissions / odors [25]

Medium	Abbrev. to	CAS No.	Danger symbol *)	MAC value**)
Carbon monoxide	CO	630-08-0	F T	33 mg/m^3
Hydrogen sulfide	H_2S	7783-06-4	F T+	15 mg/m^3
Hydrogen cyanide	HCN	74-90-8	F+ T+	11 mg/m^3
Ammonia	NH_3	7664-41-7	T Xi C	14 mg/m^3
Hydrogen chloride	HCl	7647-01-0	C T	8 mg/m^3
Phenol	C_6H_6O	108-95-2	T	7.8 mg/m^3
Benzene	C_6H_6	71-43-2	F T	-
Toluene	C_7H_8	108-88-3	F Xn	190 mg/m^3
Xylene	C_8H_{10}	100-41-4	F Xn	221 mg/m^3
Naphthalene	$C_{10}H_8$	91-20-3	Xn	50 mg/m^3
Polycyclic aromatic hydrocarbons (PAH)	-	-	***)	***)

*) conforming to the list of substances according to Annex I of Directive 67/548/EEC [25]
**) Limit Values Regulation as the daily average [26]
***) according to the safety data sheet of the respective substance – pure material and component mixture (tarry compounds and condensable compounds) and §6 Limit Values Regulation 2003, Annex 1: MAC values for hydrocarbon vapours [26]

The poly-aromatic hydrocarbons listed in Table 3-4 have been classified by international medical panels of experts [27] as health-damaging and environmentally harmful substances. These substances can occur in gasification plants in various concentrations depending on the type of process. For this reason, the use of appropriate protective clothing is categorically recommended when handling sediments, residues and liquids from biomass gasification facilities and when performing maintenance operations.

In biomass gasification plants process media can be in solid, liquid or gaseous aggregate state. The listing above cites a number of substances that can have a noxious effect on the human organism – the consequences extend from symptoms of poisoning and suffocation already after a short-term effect to genotype mutation after a long-term effect as well as through frequent contact with these substances.
Particularly those constituents are pointed out that can induce symptoms of poisoning or suffocation already after a short-term effect. These are primarily gases and vapours (vapours from waste water treatment, producer gas components such as carbon monoxide, carbon dioxide, methane, etc.) from various devices in the gasification plant. In safety engineering one predominantly assumes the hazardousness of these materials with regard to fires and explosions, which can have a very great effect on the technical facilities of a plant and the operating regulations - equally great effects are had by the preventive measures that must be implemented to reduce the health-damaging risk consequences for the technical facilities and the composition of operating and maintenance regulations in particular.

Table 3-4: Listing of carcinogenic PAH [27]

	Designation	Acronym	Molar mass [kg/kmol]
1	Naphthalene	NAP	128
2	Acenaphthene	ACY	154
3	Acenaphthene	ACE	154
4	Fluorine	FLO	166
5	Phenanthrene	PHE	178
6	Anthracene	ANT	178
7	Fluoranthene	FLU	202
8	Pyrene	PYR	202
9	benz[a]anthracene	BaA	228
10	Chrysene	CHR	228
11	benzo[b]fluoranthene	BdF	252
12	benzo[k]fluoranthene	BkF	252
13	benzo[a]pyrene	BaP	252
14	dibenz[ah]anthracene	DBahA	252
15	benzo[ghi]perylene	BghiP	276
16	indeno[1,2,3-cd]pyrene	ID	276

Important points that have to be considered:

- compliance with the relevant regulations when dealing with residues to protect health and the environment
- determination of the constituents depending on the gasification process being applied
- conditioning of the condensate/waste water

- recyclability of residues into the process
- remaining residual materials must be disposed of / processing for preparation for disposal/deposition
- compliance with emission limits for materials that must be removed
- health hazards (danger of suffocation, contamination with residues and condensates)
- danger of fire and explosion

4 Gas cleaning – an overview

In biomass gasification plants the system components are used to clean process gas for the purpose of attaining specific clean gas quality parameters of the generated producer gas for subsequent utilization. The presently used gas cleaning systems are based on the application of processes adapted from de-dusting and washing of process gas, which interact to fulfil the requirements of biomass gasification plants (dust- and tar loading). The systems are differentiated according to the following factors:

- the pollutant fraction in the process gas (dust, tar, heavy metals, alkali- or alkaline earth metals, permanent pollutant gas, etc.) to be eliminated
- process media (dry, wet, half-dry, etc.)
- separation mechanisms
- operating temperatures and pressures
- separating efficiency

For biomass gasification plants there are systems that utilize either a separate or a 1-step tar- and particle separation process. With a view to operating temperatures, separate (2-step) particle and tar separation takes place in individual devices – dry de-dusting and wet gas scrubbing are carried out in this regard. In carrying out gas de-dusting and tar washing separately, certain temperature regimes must be maintained in order to prevent tar condensation – depending on the type of gasifier and the operating state different condensation temperatures can be expected (between 150 and 250°C).

The 1-step gas cleaning process takes place by means of solvent- or water quenching for combined gas cooling and cleaning (de-dusting and tar washing). De-dusting by means of gas scrubbing processes is, however, bound to certain separation efficiencies (see Figure 4-1), which make it difficult for the gas generating unit to function stably and to attain clean gas purity limits in internal combustion engines. In addition, greater demands are made on washing media treatment. The classification given in Table 4-1 below is differentiated into systems of hot and cold gas cleaning for treatment of dust and tar. An overview of the typically used processes can be found in Figure 4-1.

Table 4-1: Classification of gas cleaning processes

Temperature range	Basic type	Effectiveness	Gas cleaning system
20 - 60 °C	Wet	Tar, particles, metal compounds, permanent pollutant gas fractions	Packed column scrubber, quench column, venturi scrubber, (wet) electrostatic precipitator (ESP), etc.
140 - 300 °C	Dry	Particles, metal compounds, pollutant gas fractions	Dust ESP, filtration deduster, etc.
300 - 800 °C	Dry	Particles, pollutant gas fractions (tar)	Filtration de-duster, dust ESP, etc.

Figure 4-1 shows the very strongly dropping separation efficiencies for the wet gas cleaning system due to the cleaning mechanism – from grain sizes of under 1-2 µm onwards it is no longer possible to attain satisfactory separation of particles from the raw gas.

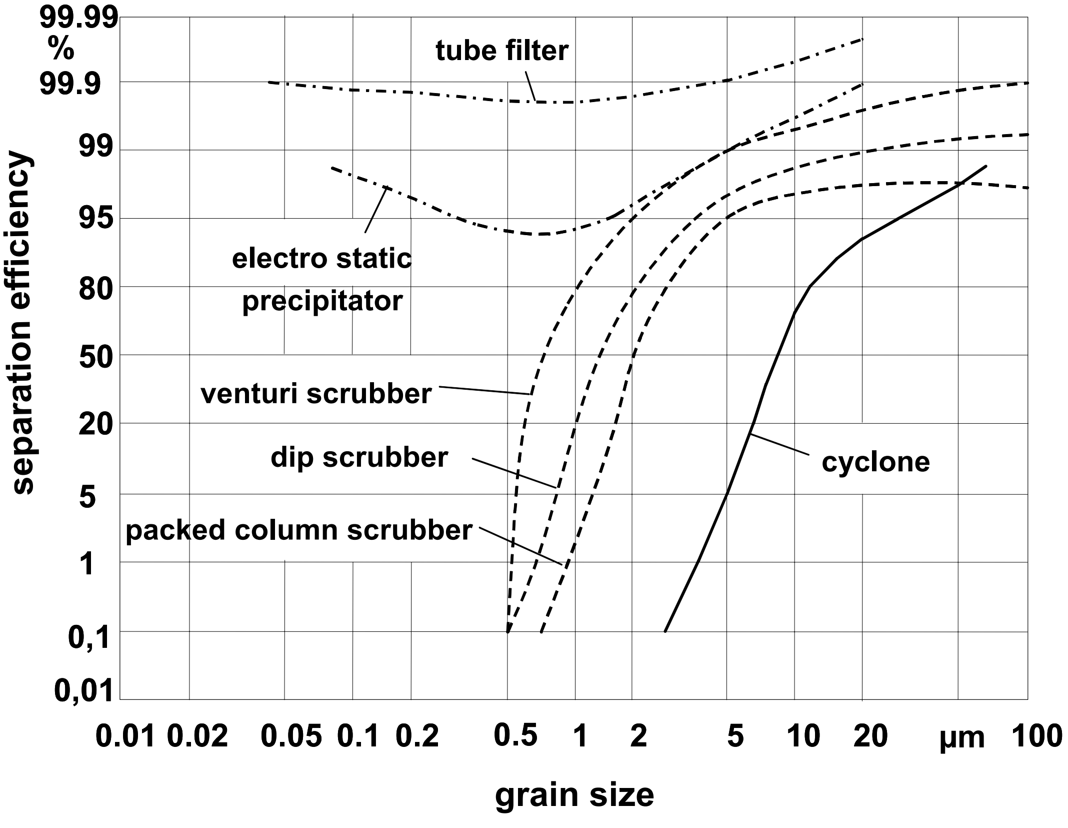


Figure 4-1: Typical separation efficiencies of gas cleaning systems [28]

The guarantee of certain separation efficiencies is a fundamental condition for the operation of a gas conditioning unit as well as gas utilization, since particle loads with regard to condensed hydrocarbon-, heavy metal- as well as alkaline and alkaline earth metal compounds can lead to malfunctions and impairments of diverse components of gas utilization systems (gas mixer, gas control and safety system, exhaust gas turbocharger, oxidation catalytic converter, etc,).

4.1 Tar treatment systems

4.1.1 Fixed bed adsorbers

Fixed-bed adsorbers provide precipitate tar from the producer gas, by the means of adsorption of high-boiling tar compounds on, e.g. activated charcoal. At room temperature a loading of the activated charcoal with aliphatic hydrocarbons of 20 to 80 $\%_{\text{Mass}}$ is reached. The fixed-bed adsorber illustrated in Figure 4-2 uses coke with a grain size of 0.56 to 1.0 mm [29].
Such adsorbers are used for tar separation, waste water processing, etc. of highly contaminated producer gases from biomass gasification plants – preferentially, such systems are utilized for analytic purposes involving media processing in the laboratory. Fixed-bed adsorbers in biomass gasification facilities were frequently used in obsolete concepts for gas cleaning operations with a bulk layer of wood chips, but are not able to fulfil present-day process requirements.

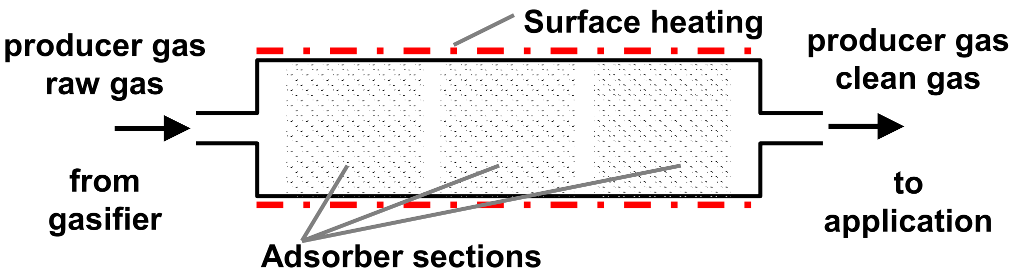


Figure 4-2: Fixed-bed adsorber for tar compounds

4.1.2 Thermal tar treatment

Thermal tar treatment systems work on the basis of partial oxidation of producer gas loaded with tarry contaminants situated after the gasifier. Partial oxidation converts tar on the expense of calorific value in the producer gas. Thermal tar treatment is rather unusual in gas cleaning – this type of tar treatment presents itself rather as a possible process step for the reduction of the tar release potential in gas production through primary measures.

4.1.3 Catalytic tar treatment systems

Catalytic tar treatment is based on the principle of tar cracking through thermochemical reactions supported by catalysts. The cracking process leads to a decomposition of tarry compounds which results in the successive formation of permanent gas phases and lighter tar compounds. In contrast to non-catalytic thermal tar treatment, where temperatures above 1000°C are needed, catalytic reactions take place at a far lower temperature level, whereby the gasifier outlet temperature level suffices for catalytic gas cleaning and can be used without a further temperature increase. Catalytic tar regeneration is in the testing phase. In application, problems are seen mainly with catalytic converter service lifetimes due to catalyst poisons present in the producer gas (sulphur compounds, heavy metals, etc.). In general, de-dusting has to be carried out prior to catalytic conversion in order to be able to provide a dust-free gas at a high temperature level for catalytic tar treatment.

4.1.4 Wet Scrubbers

Wet scrubbers (or separators) can basically be classified into four groups that are relevant for the application of biomass gasifier plants (Figure 4-3):

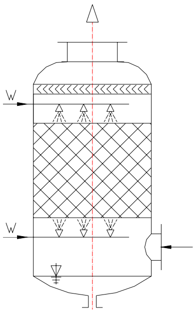
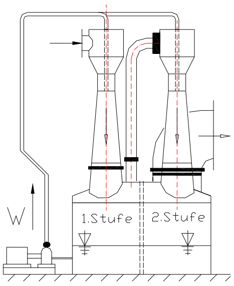
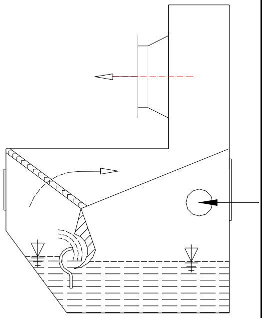
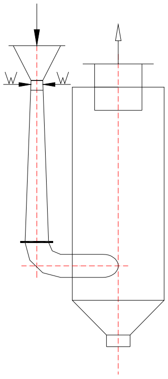
Type	**Packed column scrubber**	**Jet scrubber**	**Dip scrubber**	**Venturi - scrubber**
				
Critical grain size at ρ = 2.42 g/cm³ in [μm]	0.7 – 1.5	0.8 – 0.9	0.6 – 0.9	0.05 – 0.2
Mean relative speed [m/s]	1	10 – 25	8 – 20	40 – 150
Pressure loss [mbar]	2 – 25	-	15 – 28	30 – 200
Washing medium/gas $\left[\frac{l*(h)}{(h)*m^3}\right]$	0.05 – 5	5 – 20	-	0.5 – 5
Energy requirement [kWh/1000m³]	0.2 - 1.5	1.2 - 3	1 – 2	1.5 - 6

Figure 4-3: Overview of wet scrubber types and their characteristics [30]

Packed column scrubbers are characterized by filling with packing materials, that are sprinkled by the washing medium. The scrubber vessels are equipped with jets that spray in the washing emulsion for the wetting of the packing. The gas to be cleaned generally goes through the scrubber as a counter flow.

In the **jet scrubber** the washing emulsion is sprayed into the scrubber vessel with overpressure. This acts to disperse the stream of washing liquid into 1-3 mm sized drops; this brings about an enlargement of the mass transfer surface area between the gas to be cleaned and the washing medium.

In the **dip scrubber** the contaminated gas stream flows through a liquid bath, where the gas stream is mixed up with the scrubbing media. The method provides good transfer of mass because of the high turbulence of the streaming gas-liquid phases.

The manner of operation of the **venturi scrubber** is based on the increase of the speed of the gas stream through narrowing the cross-section and simultaneous spray injection of a washing liquid. The resulting high shearing forces between the gas and the liquid lead to an extra fine distribution of liquid drops, which agglomerate with the solid particles. On account of their mass moment of inertia the agglomerates are precipitated out of the gas stream through impact separation in the downstream droplet separator (demister).

Various washing agents are used as **scrubber emulsions**. The spectrum of washer media used ranges from pure water up to oil-water mixtures dependent on the pollutants that are to be eliminated. The use of water as a washer medium shows unsatisfactory results with regard to regeneration efficiency and continuous operation behaviour. Crucial disadvantages in using water as a washing medium involve saponification, the low solubility of hydrocarbon compounds, surface tension effects, the clogging of apparatuses and the comparatively problematical expense of waste water processing.

Scrubber oil emulsions act in the application as solvents, which support the effect of cleaning with regard to tarry compounds and protect the apparatuses themselves from clogging. The tar-loaded solvent can be used in the circuit as a washing agent. Through the regeneration of tarry compounds and the condensation of steam out of the process gas the washing emulsion is enriched with tarry compounds and contaminated waste water. Fractionation of the washing emulsion is accomplished by suitable separation of the water phase from the oil phase. Waste water accumulating in this manner must be subjected to proper processing or disposal. The separated oil phase can be used further up to the saturation with tarry compounds and must then be subjected to controlled recycling or disposal.

4.1.5 Wet ESPs

Besides the possibility of the use of dry ESPs (Figure 4-9), there is also the possibility to use wet ESPs [31], [32]. This apparatus offers advantages regarding aerosol separation (condensing tarry compounds, dust particles, etc.). The agglomerations (dust and tar load) on the collecting electrodes can be removed with the washer fluid. Attention must be paid to the accumulating pollutant mixture of particles and condensable load, etc., the processing of which requires additional expense.

4.2 Dust treatment systems

4.2.1 Dust ESPs

Dust ESPs are based on the utilization of the effects of mass moments of inertia due to deceleration- and acceleration forces that affect particles of various sizes. The particles are caused to make contact and to collide with one another at/with the inner surfaces of components and are thus decelerated. The retardation and deflection from the main gas stream cause the separation of the particles from the main gas stream and they sink to the bottom of the precipitator.

4.2.1.1 Impact and deflection separators

Due to the effect of gravity, it is difficult to separate particles from gas streams. However, gravity can be intensified through the forcing of additional centrifugal forces. The required centrifugal forces can be generated by a single or multiple deflection of the stream – this brings about total forces acting upon the particles that can amount to a multiple of gravitational force. In the case of the impact separators this force is used to separate the particles. By deflecting the gas stream on baffle plates the particles are diverted from the direction of the stream because of their inertial force and separated on the baffle plates – from there they then sink due to gravity into a dust chamber at the bottom of the precipitator.

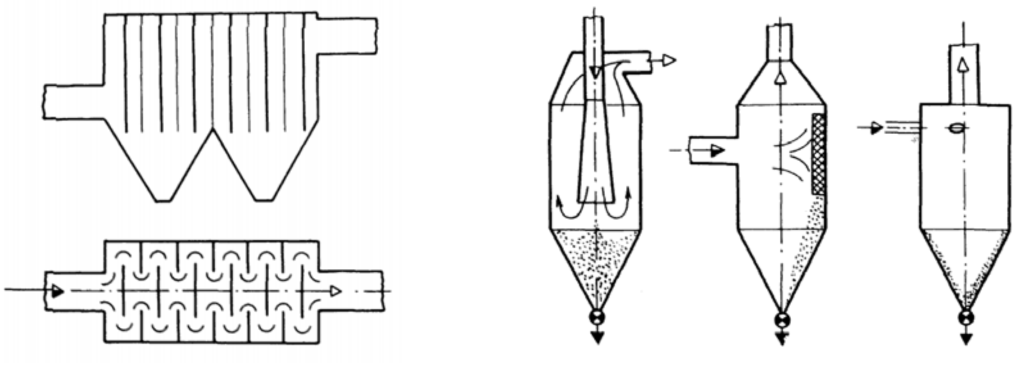


Figure 4-4: Impact separator and deflection separator [33], [34]

4.2.1.2 Cyclone (or centrifugal) separator

Figure 4-4 shows the basic construction of cyclone separators [35]. The gas/solid mixture to be separated is fed tangentially or axially into a cylindrical receptacle with usually a conical underpart. The swirl is produced either through the tangential entry of the gas or through guide vanes attached to the circumference of the cyclone housing. Through the rotary stream forming in the separation chamber centrifugal forces act upon the solid particles and centrifuge them outwards. The solid material slides down the wall of the cyclone separator into a collecting vessel. The gas rotating in the interior of the separator is drawn off upwards through a conical or cylindrical dip pipe.

Due to the simple construction, the low pressure loss of the separator and the good characteristics regarding separation of coarse particles (5 to 10 µm), cyclone systems are used in plants in most cases only as pre-separators for gas cleaning and can be used in the hot gas area of the plant on the basis of a temperature-resistant construction. When designing and dimensioning for high gas temperatures it is necessary to pay attention to the reduction of separation efficiencies (increase in viscosity).

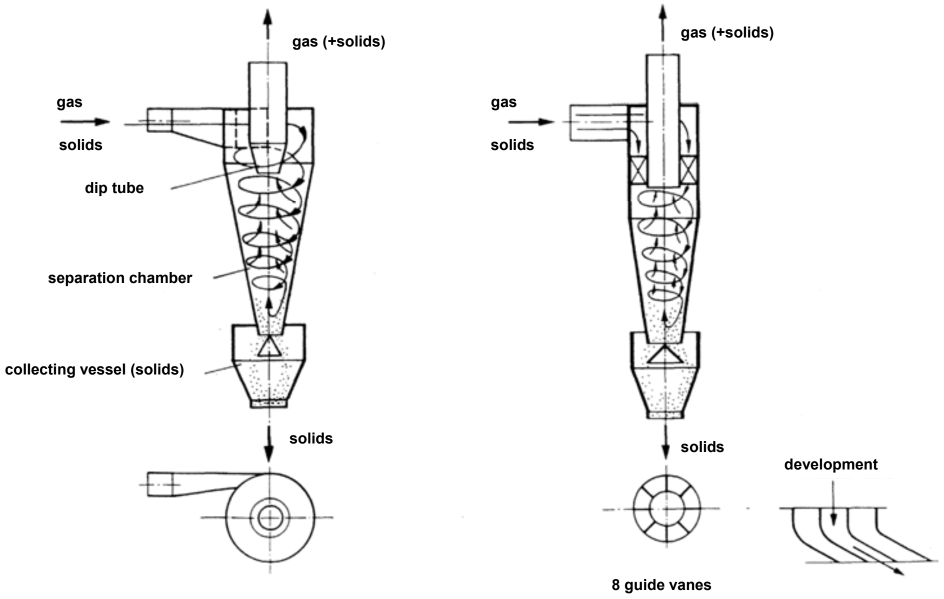


Figure 4-5: Cyclone separator with tangential (left) and axial swirl generation [35]

4.2.2 Filtration de-duster

A common feature of all filter-type separators is the use of filter media that fulfill a collector function, e.g. gas-permeable fabric or gas-permeable, porous sintered materials. The gas to be cleaned is passed through the filter medium; several mechanisms bring about the separation of the particles in the filter that are transported in the gas stream. A differentiation is made between surface- and deep-bed filtration – if separation takes place inside the medium, one speaks of deep-bed filtration.

In the operation of such filtration units a dust layer is formed on the surface (filter cake) of the filter medium. The constant accumulation of particles on this surface is designated as surface filtration [31].

On the inside of this filter cake, depending on the grain size distribution of filtered dust particles, a porous surface layer is formed that offers a filter medium with good characteristics for the separation of small and ultra-small particles.

4.2.2.1 Baghouse (or tube) filters

The baghouse filter is presently one of the most customarily used surface filters. The raw gas enters the filter chamber from below, flows through the filter tubes from outside to inside and exits the chambers on the upper side. To remove the filter cake deposited on the outside of the filter tubes, with this particular type a short pressure surge of scavenger gas is directed against the stream of raw gas (from inside to outside) – see Figure 4-6.
Besides regeneration by means of impulse jet, also vibration regeneration is used. Depending on the structuring of the plant, regeneration can be carried out in the “online” mode (type with a filter chamber) and in the “offline” mode (type with at least 2 filter chambers). Here the chamber to be regenerated is sealed off from the supply of raw gas by means of a valve and the deposited dust cake is removed by shaking, vibrating or the use of impulse jet regeneration of the tubes. Removal of the filter dust particles is by means of suitable conveyor systems.

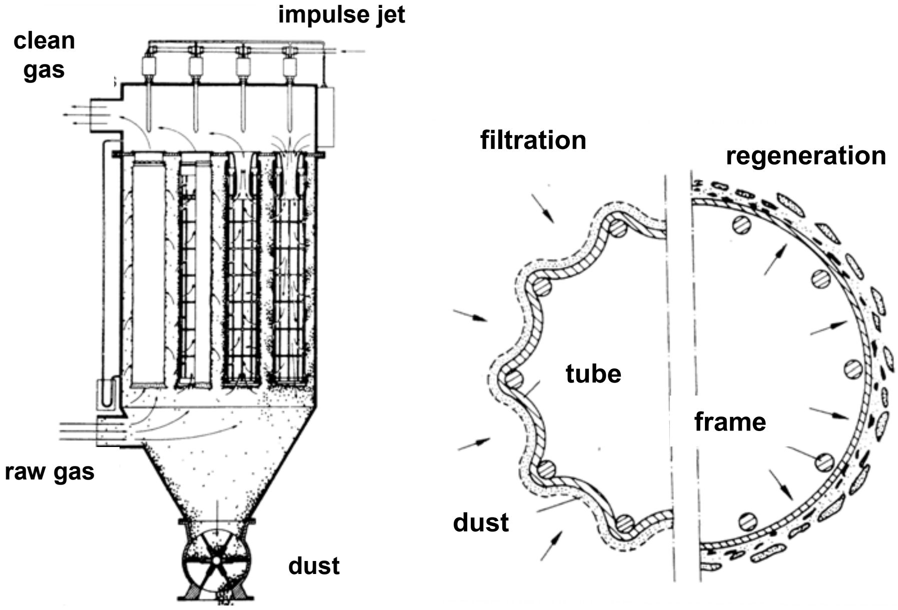


Figure 4-6: Baghouse filter system with pressure shock regeneration [35]

The main parameter influencing pressure loss is filtration duration. The particles separated over a period of time form a filter cake that causes a loss of pressure, but, as mentioned above, one that represents a filter medium for depth filtration. The pressure loss ranges from 2 to 15 mbar. After reaching the specified maximal pressure loss the filter cake is regenerated by the filter medium. Filter materials that are used are fabric, fleeces and felts. Depending on the task definition and the general application conditions, e.g. operating temperature, pre-coating agent, grain size distribution, etc., these can consist of a great range of materials (see Table 4-2).

Table 4-2: Temperature stability of typical filter media [32]

Temperature	Typical filter material
< 100 °C	Cotton, PVC, polyester
150 – 300 °C	PTFE, glass fiber felt
300 – 600 °C	Fabric, fleeces and felts of metallic, ceramic (alumina silicates) and mineral materials, quartz, glass and graphite
> 600 °C	Fabric, fleeces and needle felts of ceramic fibers or quartz fibers, grain ceramics of alumina silicates or silicon carbide (SiC)

Since the formation of a filter cake (that can be easily separated by the filter medium) is a prerequisite for satisfactory operating behaviour regarding pressure loss and separation capacity, with very fine dust particles it is often necessary to apply a precoating layer of pulverised lime stone, activated charcoal, etc. to the fabric filter prior to filtration. This replaces the filter cakes that are necessary for filtration but missing, strengthens filtration properties and serves to protect the filter tube material.

For the separation of fine and simultaneously sticky particles a permanent dosing of an inert aggregate (e.g. stone meal) may be necessary in addition to pre-coating. While the former protects the filter medium from the penetration of particles and should guarantee good regeneration, the latter ensures the formation of a loose, porous dust cake that allows flow-through with little pressure loss.

4.2.2.2 Multi-layer filter candles (or cartridges)

Multi-layer filter candles consist of a metallic (medium to high temperature) or ceramic (Al_2O_3, SiO, MnO – high temperature) permeable base material. The filter medium in this case is a rigid and porous body whose inter-grain spaces allow gas to pass through, but prevent a wandering of dust particles (dependent on grain size distribution). The porous filtration matrix therefore indicates smaller inter-pore space dimensions than the smallest dust particles to be filtered out. By covering the tube filter with pre-coating agents, dusts and aerosols to provide a second filtration layer (surface filtration), the filtration effect is intensified and good separation efficiencies are attained. These filter systems can be used at temperatures above 500°C and attain very good separation efficiencies.

Regeneration in such filter systems is carried out by means of a pressure pulse. On account of the rigid filter media the regeneration effect on the dust filter is not supported by an elastic movement of the filter medium (e.g. tube filter regeneration – regarding the movement of the textile membrane, see Figure 4-6). The separation of the filter cake is therefore effected only through the pressure pulse of the regeneration gas, which necessitates the expenditure of considerably greater amounts of scavenger gas (nitrogen, carbon dioxide, etc.).

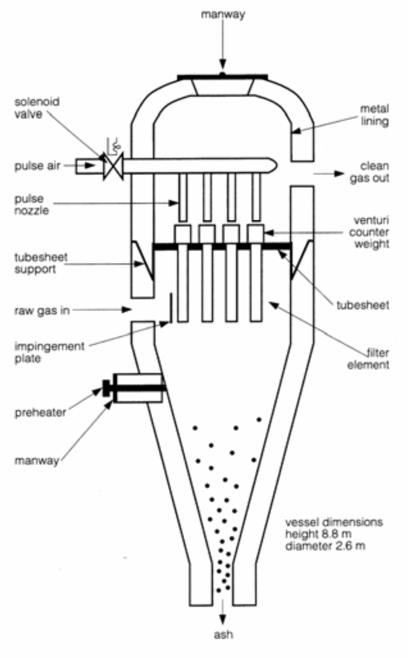


Figure 4-7: Multi-layer filter candle [28]

4.2.2.3 Ceramic cross-flow filters

Figure 4-8 presents a ceramic cross-flow filter. This is differentiated mainly by its geometry and the directing of the gas streams through the filter medium. A decisive advantage results through the 7 (to 10) times greater ratio of filter area to filter volume due to the more complex geometry. Separation capacity, pressure loss and regeneration type are comparable with those of the candle filter.

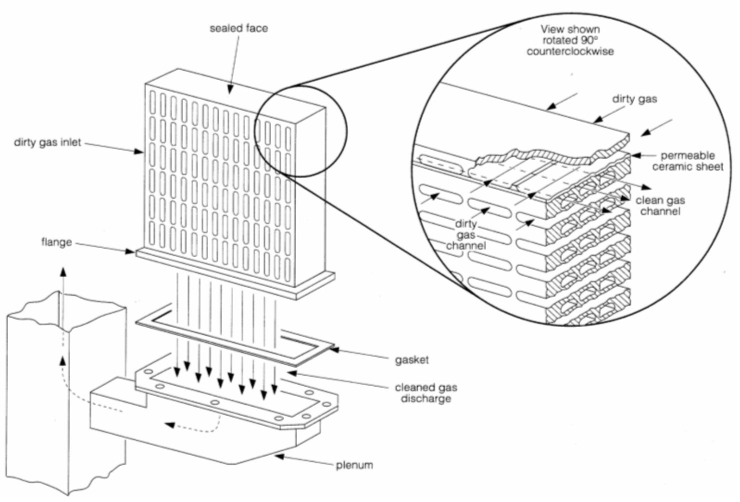


Figure 4-8: Ceramic cross-flow filters [28]

4.2.2.4 Electrostatic precipitators (ESPs)

Particle separation in ESPs is based on the effect of force on electrically charged particles in an electrostatic field – the regeneration operation is characterized by three basic processes:

- electrical charging of the particles
- separation of the charged particles by electrostatic forces of attraction in an electrostatic field.
- removal of the separated dust from the collecting electrodes

The dust particles enter the pipe-shaped ESP filter from below and are charged in the electrical field in the first few centimetres of their movement. The charged particles are attracted away from the pipe wall by the electrical field – see Figure 4-9.

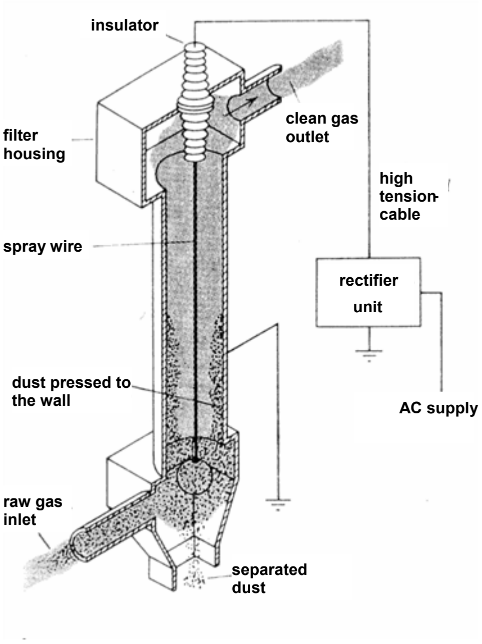


Figure 4-9: Schematic configuration of a 1-step ESP [36]

The separation effect in ESPs is described by the Deutsch equation [31], [32]. This calculation rule permits the estimation of the degree of dust separation in dependence on the filter surface area, the mean particle migration speed and the gas volume flow rate.

4.3 Summary – gas cleaning

The present state of gas cleaning in biomass gasification shows, that the usage of today available technologies offers technically solutions to clean polluted producer gas in compliance with requirements necessary for gas utilisation.

Many companies offer gas cleaning systems that include a concept for wet gas cleaning with downstream droplet separation and bulk filling layer filtration (bulk filling of wood chips, etc.). However, these systems are not practical because the requirements specified for the required gas purity regarding alkali-, alkaline earth- and heavy metal compounds, etc. in combination with the utilization of special gases (mixture formation, secondary treatment of exhaust gas, etc.) are normally not fulfilled.

Due to the experience gained, when constructing biomass gasification facilities one should fall back on already tested technological concepts – appropriate experience in this context is already available regarding the operation of staged gas cleaning systems for separate de-dusting and tar washing (pre-coated fabric filters with subsequent tar washing) as well as combined systems of quenching and wet ESPs. Due to the investment and operating costs to be covered and the accumulating mixed residue fraction of the gas cleaning overall (aqueous and hydrocarbon-bearing condensate, particle sludge, etc.) the latter makes great demands on integration in the plant concept (treatment of residues), the management of the plant, etc. While interesting new technologies have come onto the gas cleaning market in the last period of time, e.g. catalytic tar cracking, no sufficient large-scale technical know-how has been published. These technologies necessitate more intensive investigation. Above all, their long-term behaviour is important, so that they can be applied successfully and economically in gasification plants.

The residual materials accumulating from gas cleaning are residues that have to be subjected to processing and recycling and partial disposal, respectively. On account of physical and chemical properties the amounts of residual materials of arising residues cannot be recycled into the process or disposed of without suitable treatment – the technical possibilities of residue treatment will be treated in the following subchapter.

5 Waste water treatment from biomass gasification plants

5.1 The origin of residues from the operation of gas cleaning systems in biomass gasification plants

In contrast to the combustion of biomass, a process in which water is formed as a product of combustion, with the sub-stoichiometrically operated, thermochemical conversion of biomass depending on process conditions - and the gasification reactions connected with that - steam is consumed as a reactant (the water turnover is in the region of 0.05 to 0.1 kg water per kg dry fuel). The excess input steam (from the fuel/gasification medium) is naturally discharged with the producer gas and represents, depending on the partial pressure and temperature in the subsequent process steps of gas cooling and cleaning, the basis for an accumulation of condensate. Depending on the respective concept of gas cooling, cleaning and mixture conditioning and their pressure and temperature control, one must reckon with an accumulation of condensate in these process steps. The condensates generated in the process of gas cooling and cleaning usually occur together with other, e.g. tarry, residues and thus increase the waste water disposal- or treatment load. Gas engine operation requires the provision of a condensate-free fuel gas mixture in order to prevent impairment of the mixture control system, internal combustion as well as secondary treatment of exhaust gas. With regard to possible accumulation of condensate the following process steps can be relevant in the entire plant:

- gas cooling (depending on heat exchange media and their pressure and temperature)
- gas cleaning (temperatures, pressures),
- exposed pipelines
- gas blower systems,
- gas engine
    - air/gas mixer of the engine in which the producer gas is mixed with the suitable amount of combustion air,
    - the gas/air mixture is compressed in the turbocharger and hereby warmed up,
    - in the intercooler, in which the compressed fuel gas mixture is cooled to increase the volumetric efficiency of the engine (please note: partial pressure problem, condensate generation!)
    - exhaust gas heat exchanger (with regard to the steam in the stream of exhaust gas formed during conversion – part load problem)
- Basically all process steps involving transient start-up and shut-down processes of the plant

The dew point of the mixture must also be taken into account, both when the mixture is formed in the air/gas mixer and when it is cooled down after the turbocharger. To eliminate condensation of the mixture, cooling down may not take place under the dew point. Figure 5-1 shows possible condensate accumulation points in a biomass gasification plant (depending on what temperature and pressure regime has been set and on the plant configuration).

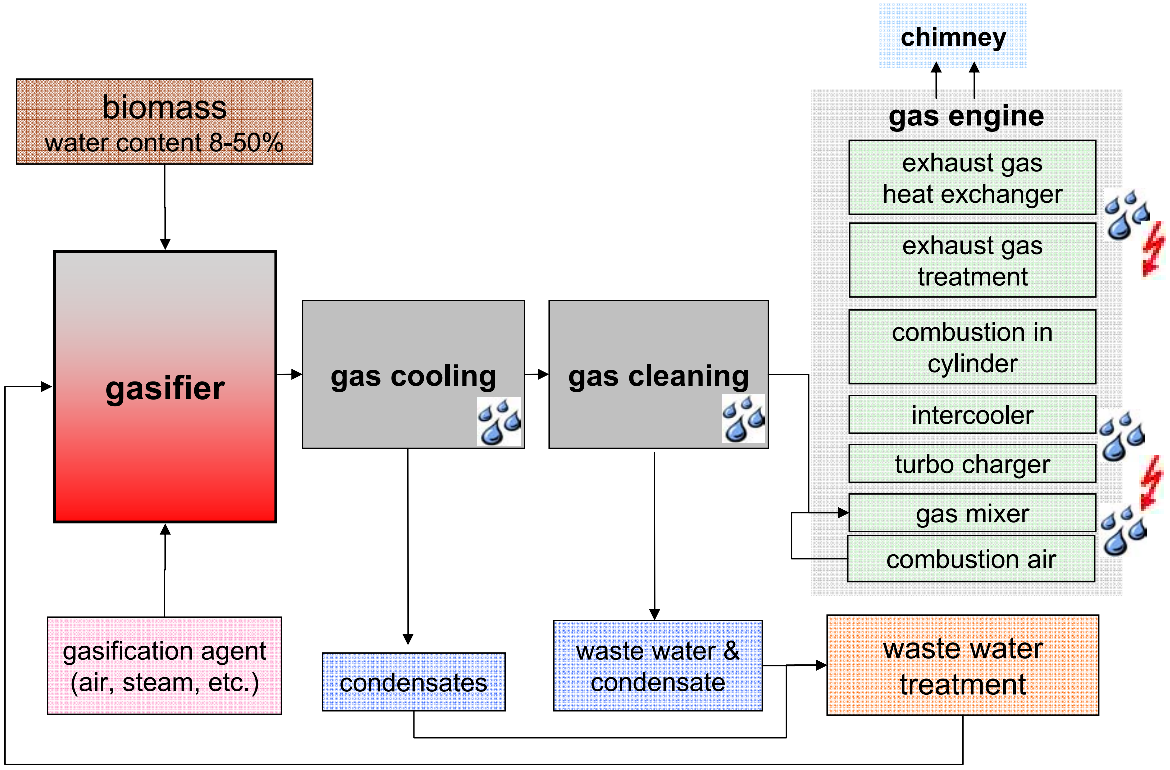


Figure 5-1: Possible condensate accumulation points in a biomass gasification plant

Basically, with regard to the waste water problem it must differentiate between

- condensate accumulation due to the temperature of the producer gas in the plant falling below the dew point and
- the gas cleaning system used (especially with wet gas cleaning systems)

In principle, there are two different approaches to avoid problems from condensate accumulation:

- professional disposal (Please note: possibly loaded with noxious constituents)
- process-internal treatment/recycling
- internal combustion
- treatment of residues by means of various waste water treatment processes
- a minimization of the condensate build-up (aqueous portion) can be counter-acted by pre-drying the fuel and setting suitable gasification parameters – considering point 1 and 2 of this list.

In the development of a concept the following data regarding the condensate balance (water and organic condensate balance) must be examined:

- the amount of water brought in with the fuel
- water conversion in the gasifier
- producer gas humidity (possible from the calculation of the dew point)
- the expected loading of the producer gas pollutions regarding organic and inorganic compounds and their dew-point
- data on the temperature during gas cleaning and the safety margins to the dew point as well as data on amounts of waste water accumulation
- calculation of the dew point in the air/gas mixer, intercooler for the air/gas mixture and specification of the temperatures to be maintained

5.2 Constituents of the accumulating condensate

Depending on the selected combination of gasification and gas cleaning technology and the set operating parameters, the aqueous condensates of biomass gasification plants contain a varying amount of inorganic and organic load. Producer gas from fixed-bed gasification processes contains mostly only small portions of inorganic dust (typically <1g/Nm³); in fluidized-bed processes, in comparison, dust portions of about 10g/Nm³ are customary. The fly charcoal portion depends on the speed at the reactor outlet and varies between 0.1 and 10 g/Nm³.

The content and composition of organic hydrocarbons depend on the type of reactor, the retention time and the temperature in the reactor. In the case of staged gasification processes the producer gas contains almost no organic compounds. With fluidized-bed- or fixed-bed gasification processes the producer gas contains greater amounts of hydrocarbons (tars), but also still considerable amounts of phenol, benzene, toluene, xylene and other aromatic hydrocarbons that are possibly found again in the accumulating condensate.

The main component of the inorganic gaseous pollutants is ammonia. Hydrogen sulfide also occurs in small concentrations. In unprocessed biomass as a fuel one can expect only extremely low concentrations of HCl (< 10ppm) [37].

In the event that these pollutants are precipitated together, e.g. in a wet ESP, all these substances can be found in the waste water and must be separated, a process that leads to increased costs regarding treatment of residues. In a separate precipitation of solid particles (e.g. by means of a tube filter) and tars (e.g. gas scrubbing with packed column scrubbers) only the organic pollutants and ammonia in the waste water have to be treated.

5.3 Waste water treatment processes

Cleaning processes in waste water treatment technology are based on chemical, physical and biological processes permitting suitable treatment of residues through conversion, re-concentration or decomposition of the waste water components.

5.3.1 Physical processes

The objective of physical processes of waste water management is to separate and re-concentrate insoluble waste water components in order to purposefully pre-condition them in a subsequent process step for recycling or disposal.
The waste water may contain dissolved and/or undissolved substances of an inorganic or organic nature in solid or fluid form. Their elimination can be carried out through the following procedures:

- static processes: e.g. sedimentation, flotation
- mechanical processes: e.g. centrifugation, filtration

Physical processes in biomass gasification facilities are often used as preliminary cleaning for the separation of solids or for separation of the organic from the aqueous phase. When using filtration processes, however, the tar portion in the waste water often causes problems due to clogging the filter units. In principle, of the various physical processes the sedimentation process is well suited to separate the major portion of tars from the condensate. Admittedly, the limits for waste water cannot be attained with this process alone.

5.3.2 Membrane processes

Membrane processes are understood to mean the removal of micro-particles to the point of dissolved substances from waste water by means of a filter located on a frame.
On account of this special position, membrane processes are classified partly to the physical and partly to the thermal processes, and for this reason are treated here as a separate section.
Since the first asymmetrical membranes appeared in the year 1960 membrane processes have developed into industrial processes of great technical and commercial importance.
In the last years membrane technology has been constantly further developed thanks to progress made in new membrane production techniques (the possibility of selective membranes as well as the increase of thermal and chemical membrane stability) and also due to improvements in module and plant design. Membrane processes have been used until now only seldom in biomass gasification processes.

5.3.3 Thermal treatment processes

Thermal processes are used to separate dissolved substances. They are based on re-concentration of the waste water components or transport in a new pollutant stream, which in most cases requires subsequent treatment.

Evaporation
Evaporation is used primarily for the concentration of non-volatile components in residue.

The proportion of solids in the waste water conveyed into the evaporator amounts usually to less than 10%$_m$. The objective is to evaporate as much water as possible so that the original solution contains a solid content of, for example, 50%$_m$.

Distillation

"Distillation" is defined as a method, which is used to separate vaporizable volatile substances from non-volatile ones and substances with different boiling points, respectively. In the distillation process the mixture of substances is brought to the boiling point. The steam is condensed and collected in distilling receivers. The boiling temperature for distillation should be in the range of 30-150°C. Compounds with a high boiling point must be distilled at a reduced pressure.

Stripping

Stripping serves primarily to separate products with high volatility, but low solubility (e.g. ammonia, fuel, halogenated hydrocarbon, etc.) from an aqueous stream. The substances are expelled from the waste water with the help of air or steam.

5.3.4 Chemical processes

Chemical processes for waste water treatment are targeted on converting inorganic and organic waste water components to the extent that they can be directly eliminated, transported into ecologically harmless compounds or so pre-treated that they can be removed in a consecutive reaction.

The following chemical processes are used:

- neutralization
- precipitation
- oxidation
- reduction
- re-concentration (ion exchange)
- complex formation
- adsorption
- extraction

Chemical processes, e.g. the oxidation of tars by means of hydrogen peroxide or adsorption of the tars on activated carbon, were investigated in a lab-scale units. However, due to the high operating costs, these processes have not yet been accepted.

5.3.5 Biological processes

The biological processes serve primarily to reduce organic substances through the metabolic activity of microorganisms. Microbiological decomposition can take place in anaerobic, aerobic and anoxic processes. During the process of decomposition the waste water components are transformed into ecologically harmless compounds or into new cell mass though cell division. Due to the toxicity of tars, biological processes are not often used as a waste water treatment technology for biomass gasification facilities.

6 Comparison of various gas cleaning concepts

In commercially operated biomass gasification plants the accumulating waste water is subjected to treatment to be able to fulfil requirements for utilization (combustion in plants, conditioning and recycling, etc.) or disposal through authorized companies. Table 6-1 shows an overview of different secondary waste water treatment concepts implemented at existing plants.

Table 6-1: Overview of concepts implemented for gas cleaning and secondary treatment of waste water of various plant concepts

	Gas cleaning process (GCP)			**Waste water treatment**	**Waste water recycling**
	Dry GCP	**Wet GCP**	**Process detail**		
Güssing	☒	☒	Tube filter and wet tar washing	Waste water evaporation	Combustion of residues in the plant
Harboøre		☒	Quench and wet ESP	Sedimentation Waste water evaporation	Combustion of residues in the plant
Wiener Neustadt		☒	Quench and wet ESP	Waste water evaporation	Disposal of residues
Pyroforce	☒	☒	Tube filter and wet tar washing	Waste water storage and disposal	Disposal of residues or utilization in the process
IWT test facility / shaft gasifier	☒	☒	Tube filter and wet tar washing	Staged waste water treatment, evaporation, vapor stripping and residue recycling	Recycling in the process, discharge of waste water into the sewer system possible
DTU test facility / 2-stage gasifier	☒		Dry gas de-dusting with tube filter	Treatment unnecessary	Recycling in the process
IWT test facility / multi-stage gasifier	☒		Dry gas de-dusting with tube filter	Treatment unnecessary	Recycling in the process

The processing of residues in the plant necessitates a fulfilling of certain requirements to guarantee steady, reliable plant operation. The following points must be taken into consideration regarding the utilisation of residues from gas cleaning and waste water treatment within the gasification process or a down stream combustion process:

- Compliance of certain temperature and air to fuel ratios to ensure complete conversion of the residues
- The utilisation or recycling of gas cleaning residues may lead to an accumulation of pollutants from organic or inorganic matter in the plant.
- Gas cleaning removes pollutants from thermo-chemical conversion and from biomass components. The recycling of such residues into the gas generation can lead to a re-concentration of pollutants in the process, since pollutants can be converted only to a certain extent.
- The infeed of gas cleaning residues may only take place up to certain mass ratios in relation to the fuel stream, up to which the reaction levels (distinct

temperature ranges in the gas generation, reaction regime, etc.) do not basically change.

In a huge number of plants both, residues treatment and recycling, are carried out through an physical stripping of the gas cleaning residues (mixture of waste water and organic or inorganic matter in sludge) to attain a higher solid content und decrease water content and organic as well as inorganic phases (e.g. stripping of light tars and ammonia). The utilization of accumulating vapours can take place in the gasifier or can be established in auxiliary combustion units of the gas generator (combustion chambers of gasifier plants) or biomass boilers and in designated high temperature zones of the gas generator.

6.1 Gas cleaning concept of the fluidized-bed steam gasification plant in Güssing

The gasification process installed in Güssing (AUT) [3] is based on the steam gasification of biomass in two coupled fluidized-beds. Figure 6-1: Fluidized-bed steam gasification with dry dust precipitation and wet gas scrubbing in Güssing shows a process flow diagram of the plant. The producer gas exiting the gasifier at about 850°C is cooled down to about 150°C in the subsequent producer gas cooler. The heat is utilised for district heating. Afterwards, the gas is de-dusted in a fabric filter. The removed dust is re-circulated (fly charcoal recirculation) into the combustion chamber of the gas generator because of its content of combustible substances.

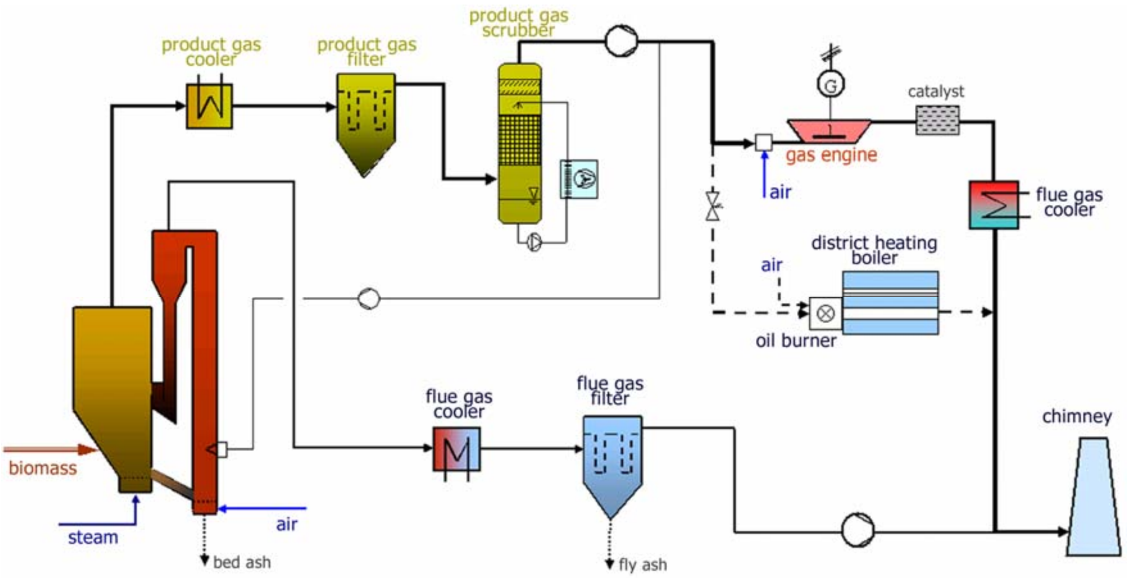


Figure 6-1: Fluidized-bed steam gasification with dry dust precipitation and wet gas scrubbing in Güssing

The downstream scrubber reduces the concentrations of tar, ammonia and acidic gas components. The producer gas is cooled down further to the temperature optimal

for the gas engine and at the same time the condensing tar and accumulating condensed water is removed, by organic solvent RME. Part of the scrubbing agent loaded with tar is continuously removed and replaced with fresh scubbing agent. The removed washing agent is disposed of in the combustion section of the gasifier. The accumulating condensate is used to produce the steam needed in the gasifier.
This special method makes it possible to recycle all residual substances back into the process; no residues or waste water accumulates during gas cleaning and cooling.

6.2 Gas cleaning concept used of the fixed-bed gasifier system in Wiener Neustadt

This particular plant of Wiener Neustadt, Austria [24] (also known as Civitas Nova) has a double fire fixed-bed gasifier with wet gas cleaning and subsequent engine utilization of the cleaned producer gas – see Figure 6-2.
After the gasifier producer gas is cooled down to 400-600°C for air preheating. Then the gas is cooled down to about 50°C with a quench. Afterwards gas cleaning takes place in a wet ESP. The cleaned gas is compressed and subsequently dried by means of reheating to prevent the temperature in the transport pipes falling below the dew point. Valves can be used to feed the gas to a flare or to the gas engine.

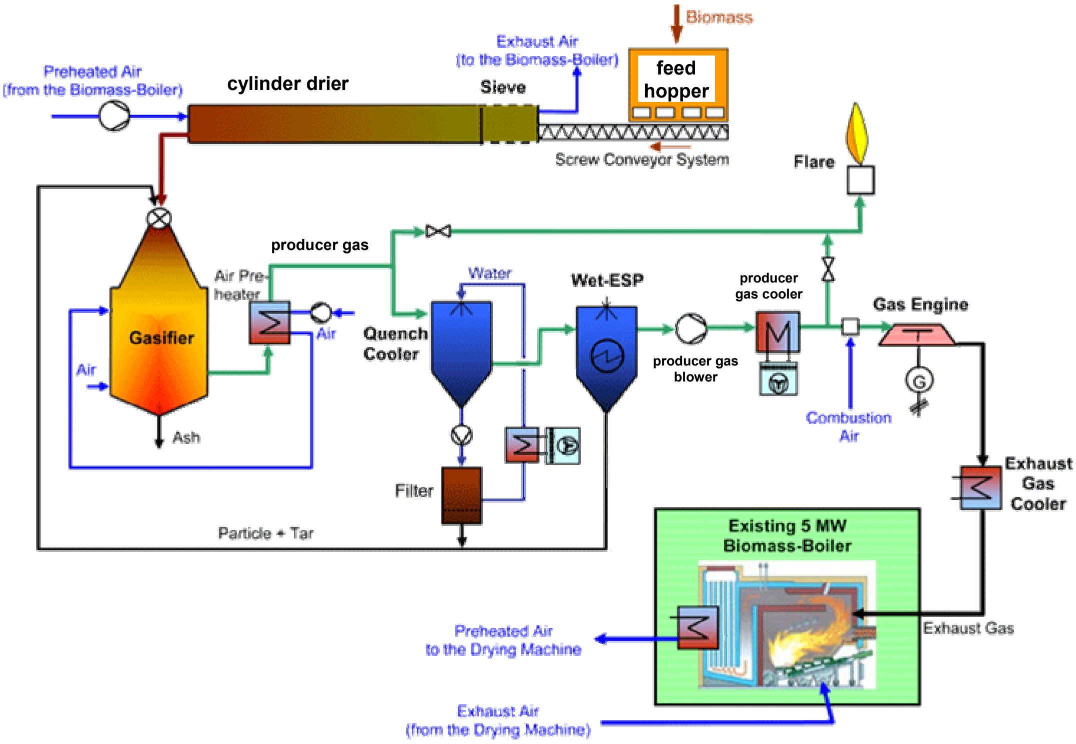


Figure 6-2: The Wiener Neustadt shaft gasification plant with a quench wet ESP and combustion of residues in an attached biomass boiler

The plant is operated either with of refeeding gas cleaning residues (tar and particles) to the gasification process (limited due to the problem of re-concentration of the pollutants in the process) as shown in the flow sheet or with thermal utilization of the

residues in the biomass furnace installed at the plant site. The recycling of plant emissions (residues from producer gas cleaning as well as CHP exhaust gas) is coupled with the operation of the biomass furnace.
For the treatment of the washing water a sedimentation- and filtration step is used to clean the scrubber media to the point that the quench- and wet ESP units can be operated continuously. Following proper treatment, the residues of sedimentation and filtration are available for recirculation into the boiler or for recycling and disposal.

6.3 Gas cleaning processes with residue treatment in the double-fire fixed-bed gasifier test facility of the Institute of Thermal Engineering, TU Graz

Figure 6-3 shows the flow sheet of the double-fire fixed bed gasifier of TU Graz and the process chain installed for gas cleaning and waste water/residues treatment (test facility with 50 kW$_{el}$, 2001).

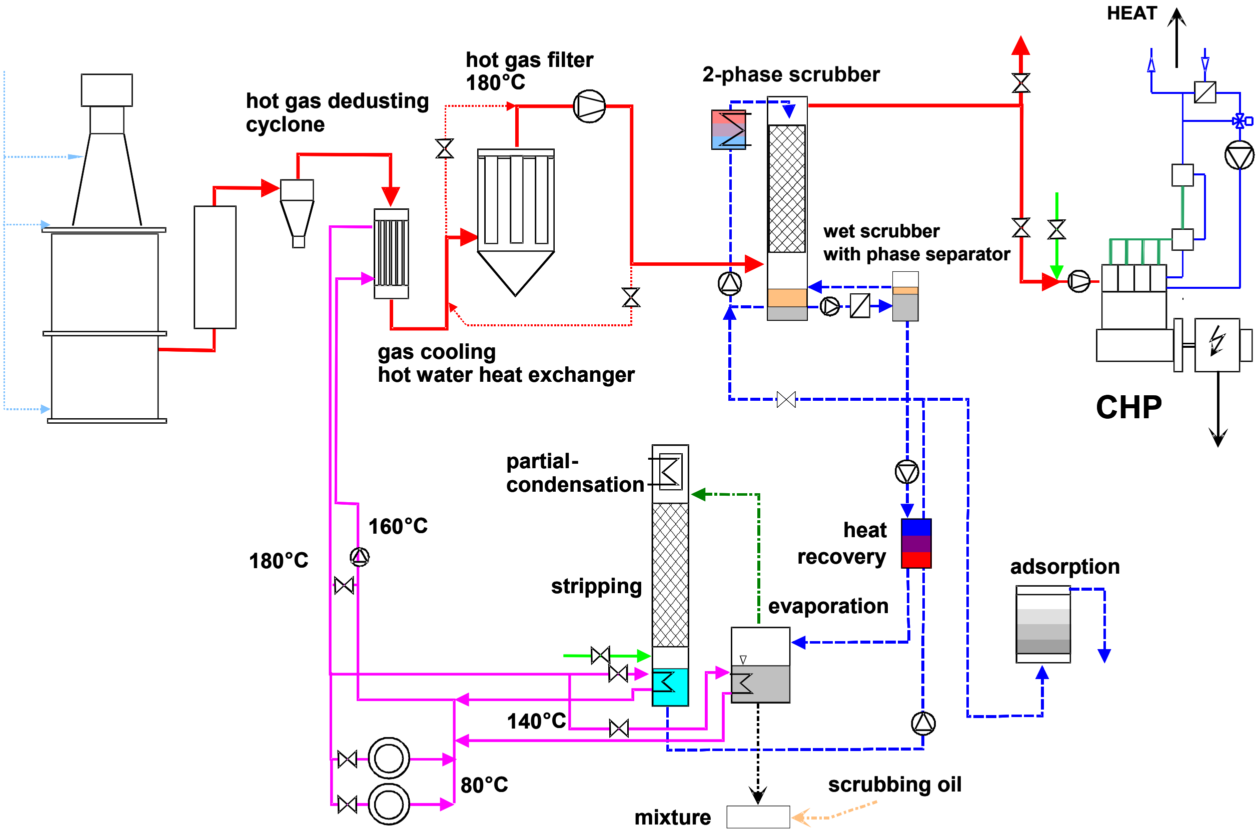


Figure 6-3: Producer gas cleaning and waste water treatment of the TU Graz lab-scale gasification facility with a double-fire fixed bed gasifier [12]

After the gasifier a start-up burning chamber is installed for post-combustion of tar only in the start-up of the gasifier. A cyclone is used for separation of course particles. Subsequently gas is cooled to about 180°C for particle removal with a fabric filter. Afterwards tar is removed in a scrubber which is operated with a mixture of water and RME. Finally gas is used in a gas engine. The waste water accumulating in the gas cleaning process is treated in a thermal conditioning unit with stripping/desorption and adsorption and can be subsequently pumped into the sewer system.

6.4 The gas cleaning process of the Pyroforce fixed-bed gasifier plant

Figure 6-4 shows the flow sheet of the fixed-bed gasifier of Pyroforce, Switzerland [38]. Gas cleaning is also separated into dry de-dusting with pre-coating and wet gas scrubbing. The separated condensates from gas cleaning are, however, stored temporarily in a condensate tank and then disposed off.

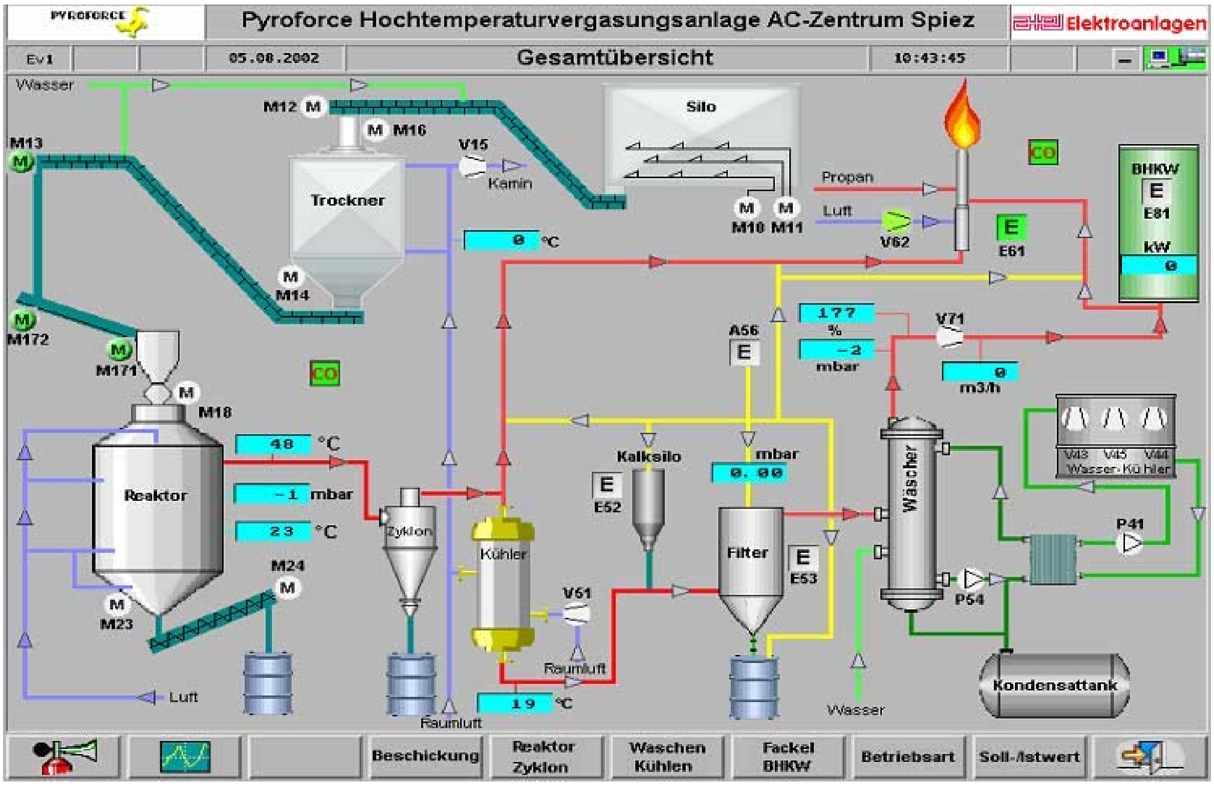


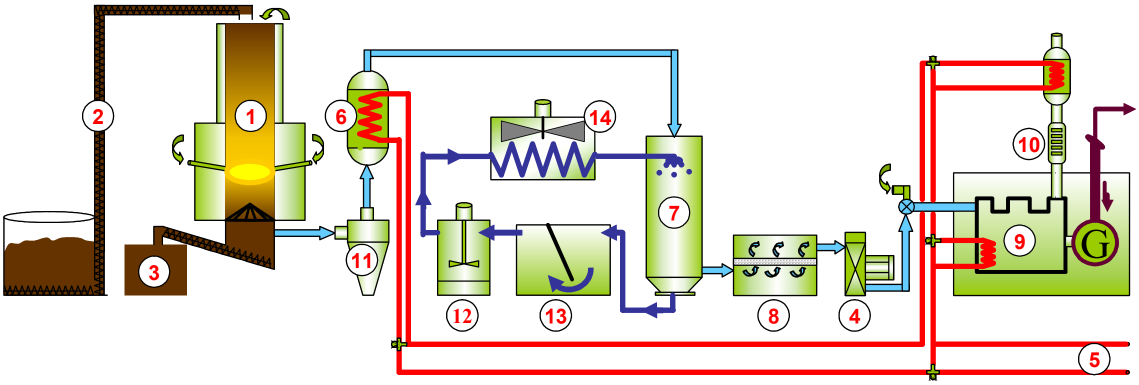
Figure 6-4: Process flow diagram of the Pyroforce test facility

6.5 Open top downdraft fixed-bed gasifier system and process chain example

An open top gasifier is a fixed-bed downdraft gasifier in which the fuel is fed in together with air at the reactor entry aperture on top.

Additional air is supplied in the middle of the reactor. The producer gas is extracted in the lower section of the reactor.

In the following the process chain according to Xylowatt [39] (Figure 6-5), where the gas is roughly de-dusted by means of a cyclone and cooled with a heat exchanger. Cleaning of the generated producer gas is by means of a scrubber system with subsequent droplet separation to bring about a precipitation of aqueous aerosols. The scrubbing water is conditioned within the plant and is available for cooling and cleaning (!) of the producer gas. As a rule, water treatment of this type (residues from wet gas scrubbing with subsequent droplet separation and solid sedimentation) does not fulfil the requirements for the discharge of aqueous gas cleaning residues from the biomass gasification plant.



1	Reactor
2	Supply of biomass
3	Ash container
4	Producer gas blower
5	District heat use
6	Heat exchanger
7	Scrubber
8	Filter
9	Gas engine
10	Oxidation catalytic converter
11	Cyclone
12	Flocculation vessel
13	Settlement tank
14	Air cooler

Figure 6-5: Open top fixed-bed gasification

6.6 *Staged gasification processes with low-tar producer gases*

In staged gasification systems such as that of DTU [40] and the TU Graz [12] the partial processes of gasification are separated into several reactors. The biomass is fed into the pyrolysis zone, where it decomposes into coke and volatile components (tars and gas components). The heat required for pyrolysis can be provided externally, e.g. from the waste heat of the gas engine. This increases the cold gas efficiency by 10-20% and hence the electrical output at the expense of usable thermal output. The volatile components from the pyrolysis zone are burned with air sub-stoichiometrically; during this process the gas is heated and partially oxidized, whereby tars are mainly decomposed. The hot gases from partial oxidation then flow through the coke layer, where a reduction of the gas phase takes place (CO_2 and H_2O to the desired components CO und H_2). In the course of this reduction also a great part of the residual tars are finally converted, resulting in a very low tar load in the producer gas (< 25 mg/Nm^3) below the tar limits for gas utilisation in engines.

A two-stage concept, as shown in Figure 6-6, is currently being demonstrated by the DTU (Danish Technical University). After gasification the producer gas is subsequently cleaned and cooled and the water is condensed out. Since the tar content in staged gasification systems is extremely low, the waste water is also hardly loaded with organic components. It was shown that condensate from the staged gasification can be disposed to the public sewer system without any further treatment [41].

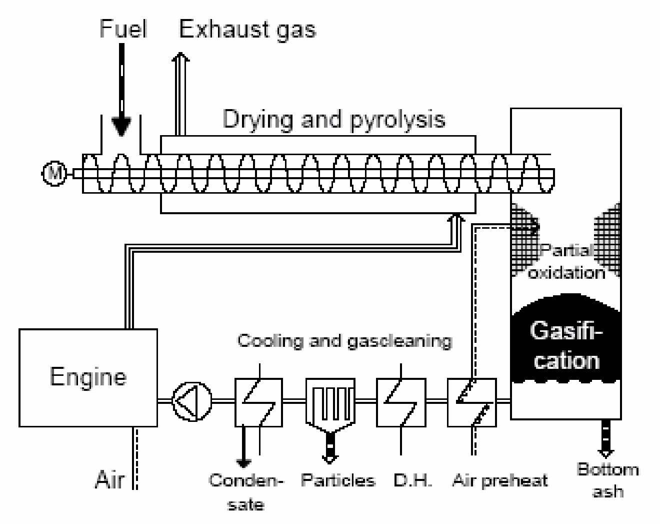


Figure 6-6: 2-stage gasification of DTU (Viking gasifier) [42]

In the staging concept investigated by TU Graz [17, 18, 43] the process step of partial combustion is carried out in a separate burning chamber. It was shown that this additional staging of the process results in tar conversion with low soot production [44]. Accordingly a raw producer gas low in tar and particulate matter can be realised. The process chain is shown in Figure 6-7.

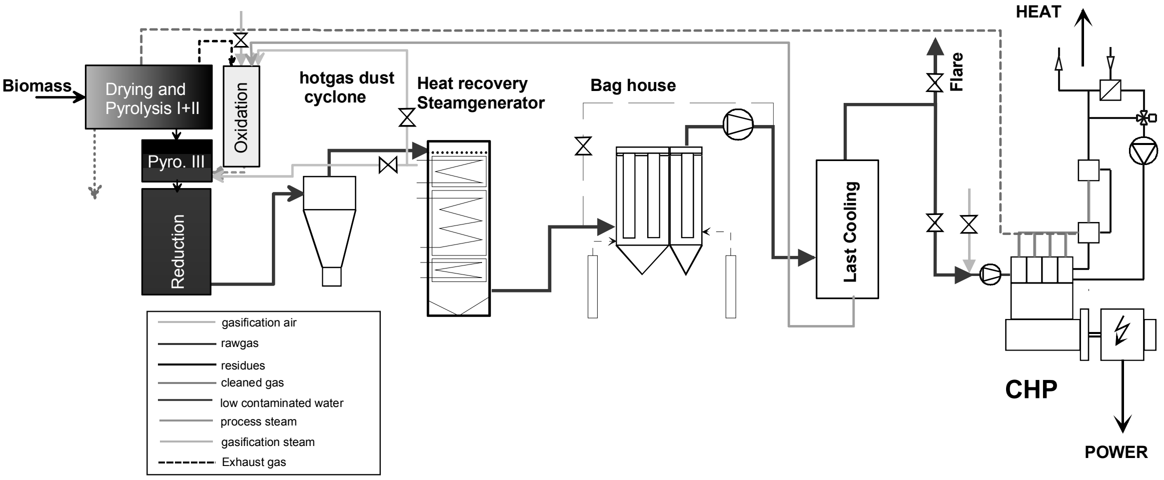


Figure 6-7: Staged gasification concept of the TU Graz with waste heat boiler, de-dusting and producer gas cooling [45]

In the first step course particles are precipitated in a cyclone, afterwards the gas is cooled to 100°C. For final de-dusting a fabric filter (with nitrogen pulsejet) is used. In the last cooling before the gas engine, the dew point of the gas (60 - 70°C) is underrun. To avoid fuel-NOx production [46] in the gas engine, ammonia should be completely removed from the producer gas here. In the test facility of TU Graz a scrubber with water (neutral, no acid addition) is used, where a high efficiency of ammonia removal can be realised. Like in the studies of DTU, ammonia was found to be the only compound in high concentration (approx. 1 g/L) in the condensate [17]. However, there is limiting value for ammonia disposal to the sewage system according to Austrian water emission law [47]. All other relevant organic (phenol index, BTX, sum of hydrocarbons) and inorganic (sulphide, cyanide) pollutants in the condensate are below the limiting value of the Austrian emission law for public sewage.

7 Gas quality requirements for utilization

7.1 Characteristics in the application of biomass derived gases

In the thermo-chemical conversion of solid biomass (e.g. wood chips) a gaseous secondary fuel is generated that, due to its heterogeneous composition, makes special demands for the application in combustion processes, as e.g. in IC engines, as well as in flare operation.

The reason for these characteristics is the composition of the gas, which consists of condensable and non-condensable components. Non-condensable, combustible components are permanent gases such as carbon monoxide (CO), hydrogen (H_2), methane (CH_4), as well as non-condensable hydrocarbons. The condensable load consists of both tarry producer gas components and steam. Each of these components indicates various combustion properties, which all together entail particular consideration in the area of gas/air mixing, engine combustion as well as secondary treatment of exhaust gas. Although difficult, the area of engine combustion is influenced primarily by external factors such as ignition energy, fuel/air mixing, etc.

The use of wood gas generally makes great demands on gas utilization modules. The CHP plants designed for use of special gases have to be adapted to the following properties of the producer gas:

- fluctuations of gas composition and thus of heating value
- fluctuations of the mass flow of the producer gas
- producer gas impurities (tarry compounds, particles, ammonia, phenol, heavy metals, alkali- and alkaline earth compounds, …)
- fuel gas components with different combustion properties (firing point, flame speeds, calorific value, etc.)

To evaluate the suitability of the produced wood gas, characteristic values can be used that can be determined directly from the quantitative composition of the producer gas. Essentially, these are the following characteristic values:

- calorific value and mixture heating value
- methane number
- laminar flame speed
- tar content
- particle content
- aerosol content

7.1.1 Pollutant requirements

Producer gas impurities represent an important factor regarding availability, operation and the service life of engine-operated CHP plants. Besides the gaseous components, which can vary in concentration depending on the gasification process, there are also undesired impurities. These impurities have organic/inorganic origin and are in their concentration dependent on the gasification process and the choice of gas cleaning process.

Besides the danger of clogging the engine, particulate matter represents a danger with regard to erosive removal of material in the area of the intake lines and valves. Erosion problems due to particles contained in the fuel gas can be reckoned with, however, only from a particle size of ≥ 2 µm onwards, which corresponds approximately to the gap size minimally occurring in combustion engines. Furthermore, one must also consider the pollution of the engine oil with dust particles and their adhesion to organic and inorganic substances (problem of clogging).

Organic compounds (tar compounds) can also condense during mixture formation/treatment on account of temperature and pressure changes. This can lead to impairment and the complete failure of a great number of system components (valves, exhaust gas turbocharger, intercooler …) due to displacement and clogging. A further problem is that of strongly polar organic compounds, which can have a strong corrosive effect on metal surfaces.

Values recommended by the manufacturers of gas utilization facilities as the permissible upper limits of such contaminants regarding various methods of energetic utilization of wood gas are listed in Table 7-1.

Table 7-1: Requirements for producer gases for IC engines and gas turbines [22], [48], [49]

	Particle content [mg/m^3_n]	**Tar content** [mg/m^3_n]	**Alkali content** [mg/m^3_n]
IC engine	< 50 (25)	< 50 (25)	n/v
Gas turbine	< 30	n/v	< 0.24

The values presented in Table 7-1 define the present state of the art. In future, engine manufacturers will raise the requirements for producer gas quality, call for more restrictive limit values with regard to dust content and, with reference to tarry compounds (e.g. potentially only a tenth of the currently permissible tar concentration in producer gas).

Such components, in combination with other producer gas components like alkali and alkaline earth compounds, are responsible for the impairment of failure-free operation. As a rule, impairment of operation involves the effects of corrosion and instability of the selected materials as well as increased wear and, as a result, increased maintenance costs.

Besides the organic compounds, which cause problems regarding fuel/air mixing and conditioning and undergo conversion in the course of internal engine combustion, the alkali- and alkaline earth compounds represent non-convertible components that can lead to specific problems in secondary exhaust gas treatment and to contamination of the engine oil.

7.1.2 Calorific value

The calorific value of wood gas, with a composition as measured in the operation of downdraft gasification processes, is about 4-5 MJ/m_n^3. This corresponds approximately to 13% of the calorific value of natural gas, whereby principally the magnitude of the mixture heating value is relevant for the gas engine (see Table 7-3). Table 7-2 shows a comparison of various compositions of wood gas with biogas and natural gas.

Table 7-2: The volumetric composition of wood gas, biogas and natural gas

		wood gas air blown	**wood gas steam blown**	**biogas**	**sewer gas**	**landfill gas**	**natural gas**
carbon monoxide	ν_{CO}	15-25%	20-30%	-	30-40%	25-35%	-
carbon dioxide	ν_{CO2}	12-25%	12-25%	15-25%	-	-	~1,4%
hydrogen	ν_{H2}	6-20%	30-45%	-	-	-	-
water steam	ν_{H2O}	2-6%	2-6%	2-6%	-	-	~ 0
nitrogen	ν_{N2}	remaining	3-5%	remaining	remaining	remaining	remaining
methane	ν_{CH4}	1-5%	8-12%	40-75%	50-60%	45-65%	96-97%

For the attainable module outputs the heating value of the pre-mixed air-wood gas mixture is very important (see Table 7-3). The significantly higher air requirement of natural gas leads to an increased thinning of the natural gas/air mixture with atmospheric nitrogen. Through this effect the mixture heating value of the wood gas/air mixture is only 33% under that of a stoichiometric natural gas/air mixture. As a first approximation, this value can be drawn on as a gauge for the expected reduced output of a natural gas engine with suitable adaptations for operation with wood gas. Table 7-3 illustrates a comparison of the composition of the mixture heating values of the individual burnable gas mixtures.

Table 7-3: The mixture heating value and the net calorific value (n.c.v.) of wood gas (air- and steam gasification), biogas, and natural gas for a stoichiometric mixture formation (λ = 1)

	Lower heating value [MJ/m_n^3]	**Mixture heating value** [MJ/m_n^3]	**Stoichiometric air requirement** [$m_{n\text{-air}}^3/m_{n\text{-gas}}^3$]
natural gas	~ 36	3.32	9.96
biogas	~23.3	3.23	6.19
wood gas/air gasification	~ 4.4	2.22	0.9
wood gas/steam gasification	~ 10.9	3.10	2.5
$^{\text{biogas}}/_{\text{natural gas}}$	65%	97%	
$^{\text{wood gas air gasification}}/_{\text{natural gas}}$	12 %	67%	
$^{\text{wood gas steam gasification}}/_{\text{natural gas}}$	30%	93%	

7.1.3 Laminar flame speed / methane number

In the case of gases with weak calorific values the laminar flame speed defines the lower limit of usability of the gas mixture in piston engines. It represents the decisive criterion for proper, complete combustion of the gas mixture in the cylinder. It is possible to use a fuel in combustion engines with a laminar flame speed of about > 8 cm/sec with an air ratio of λ = 1. The relation given below (Equation 7-1 [50]) can be drawn on for determination of the laminar flame speed u_0 as a function of the gas composition and the adiabatic flame temperature of a gas mixture).

$$u_0 = \frac{(0.13 * t_a - 108) * v_{H_2} + (0.016 * t_a + 18) * v_{CO} + (0.043 * t_a - 44) * v_{CH_4}}{v_{H_2} + v_{CO} + v_{CH_4}} \qquad \text{Equation 7-1}$$

ta … adiabatic flame temperatures in a state of equilibrium [°C]
u_0 … laminar flame speed [cm/s]
v_i … volume fractions of the combustible components CH_4, H_2 and CO [$\%_V$]

Using Equation 7-1, the laminar flame speed of wood gas (air blown) can be reckoned for stoichiometric combustion (λ = 1) and an adiabatic flame temperature of t_a= 1500°C to u_o = 39 cm/s. The speed of a methane flame under stoichiometric conditions is 36 cm/s. Comparison of these two values shows that the use of the producer gas in a gas engine regarding the combustion behaviour of the mixture should not be a problem. The influence of the high flame speed of hydrogen on the combustion of wood gas is curbed by the high portion of inert gases such as N_2, H_2O and CO_2. In the process of conversion of the fuel in combustion engines the gas mixture is subjected to the influence of pressure increase through the compression in the cylinder.

The increase in pressure leads to a reduction of the laminar flame speed, which is dependent on the type of fuel, excess air ratio, expended ignition energy, etc. [51].
The upper limit of usability of gas mixtures is determined by their tendency to self-ignite, i.e. knock tendency. The carbon dioxide content inhibits the knock tendency of the fuel mixture. Regarding the knocking limit, the methane number is indicated as a parameter for permanent gas mixtures. It indicates the knocking characteristic of a fuel gas in comparison to a hydrogen/methane mixture. Hydrogen has a methane number of 0. Pure methane has a methane number of 100. A methane number of 70 is given as the lower limit for the use of a gas mixture in a gas engine. The knock tendency is determined primarily through the content of fast burning components like hydrogen – the laminar flame speed of hydrogen is u_o = 190 cm/s with an adiabatic flame temperature of t_a = 2300°C. Through the specific composition of wood gas (relatively high portion of steam, a high portion of slow burning CO) knocking does not represent a serious problem for the use of this fuel in a gas engine. The methane numbers of wood gases lie in the range of about 87-92. Nevertheless, should the knocking limit be exceeded, various measures can be used to counteract the knocking problem, e.g.

- retarding the ignition point
- reduction of the engine load and/or the compression ratio
- increase of the air ratio
- reduction of turbocharging and the mixture temperature

7.2 Gas utilisation with internal combustion engines

7.2.1 Introduction

Producer gases from biomass gasifiers are being implemented predominantly in combustion engines. The reasons for this application lie mainly in the high power density of the engine-generator heat extraction system with suitably high degrees of electrical and overall efficiency. The utilization of wood gas in combustion engines, however, has encountered certain process-specific limits, which will be treated subsequently. Figure 7-1 presents the principle concepts for the utilization of wood gas in IC engines.
The application of a respectively selected engine concept entails technical adaptation to the requirement of malfunction-free operation of the CHP facilities. For the application of the gas-Otto engine a not insignificant expense will be necessary to ensure constant gas qualities and purity levels in the area of gas conditioning. The availability of the plant depends substantially on the constancy of the processed gas quality as well as on the various gas control- and treatment components. The quality of the air/fuel mixture determines not only the development of the output of the gas-Otto engine, depending on the chosen engine management principle (lean-burn concept, Lambda-1 concept), but also substantially the formation of emissions in the process of internal engine combustion.

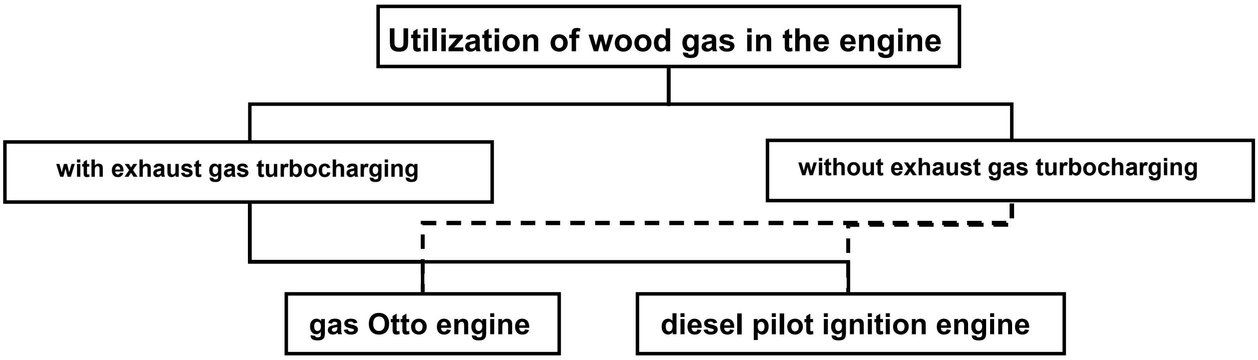


Figure 7-1: Engine concepts for the utilization of wood gas, [52], [53], [54]

The diesel pilot ignition engine injects a diesel ignition spray that effects internal engine ignition and the internal combustion of the wood gas/air mixture. This ignition spray is varied within certain limits depending on the output requirement of engine management and the processed wood gas quality and thus serves in part as a backup against engine failure in the event of fluctuations in gas quality – this facilitates the use of a qualitatively more inferior wood gas (fluctuating composition of the producer gas).
The use of diesel pilot injection technology in a small output range is connected with certain difficulties regarding a limited emission of pollutants. In the application of the diesel pilot ignition concept, the basic problem of the release of emissions when using special gases is superposed by the formation of emissions through the concurrent combustion of the diesel ignition oil, whereby on the one hand higher emission values can be expected (in comparison to gas-Otto engines) and, on the other hand, e.g. in Germany, this problem of the higher emission level is counteracted by higher emission limit values. To achieve these limit values, a number of secondary exhaust gas treatment systems is necessary, which allow operation of such plants in the high output range to appear sensible. Diesel pilot injection technology requires the use of ignition oil - as a rule on the basis of a non-renewable energy source. For the operating instructions of eco-energy plants regulations exist at present for the handling of these energy sources, which entail a reduction of the compensating amounts of eco-energy. For the future, the obligation to completely renounce the use of fossil energy sources in eco-energy plants is becoming apparent – the use of ignition oils from renewable energy sources (RME, vegetable oils) is being considered, but this stipulates similar and more difficult conditions for gas utilization modules in biomass gasification facilities with regard to operating characteristics, emissions, etc.
Both systems can have the possibility of exhaust gas turbo charging, which is important for increasing the efficiency on the basis of the increased BMEP combined with the high energy conversion density of the combustion chamber.
Due to incomplete combustion/slip (CO, C_xH_y) and/or NO_x formation of the utilized fuel/air mixture these energy transformation systems require secondary exhaust gas treatment to be able to comply with the targeted emission limiting values.

7.2.2 System elements of the gas engine (block heat and power) plant

For the utilization of special gases in gas engine (block heat and power) plants a number of aggregates are required in addition to the actual power generator, the gas-Otto engine or pilot injection gas engine. Figure 7-2 presents the system elements of such a plant schematically. It includes the mass/energy input flows of fuel (wood gas, ignition oil, diverse auxiliary power) and combustion air (dust-free, temperature-conditioned) – a specific requirement of conditioned fresh air exists alongside the supply of the combustion engine also for the aeration of the engine room. Exiting mass and energy flows include effective heat, electrical energy, engine exhaust gas and, if applicable, non-usable waste heat from auxiliary cooling.
The system elements are presented schematically in Figure 7-2. Fuel power is converted in combustion engine with generator into electric power and usable heat, which is derived from the exhaust gas heat exchanger and the engine block oil cooler. For the operation of the CHP plant, fuel/air mixing and secondary treatment of exhaust gas represent the part of the plant relevant for emissions.

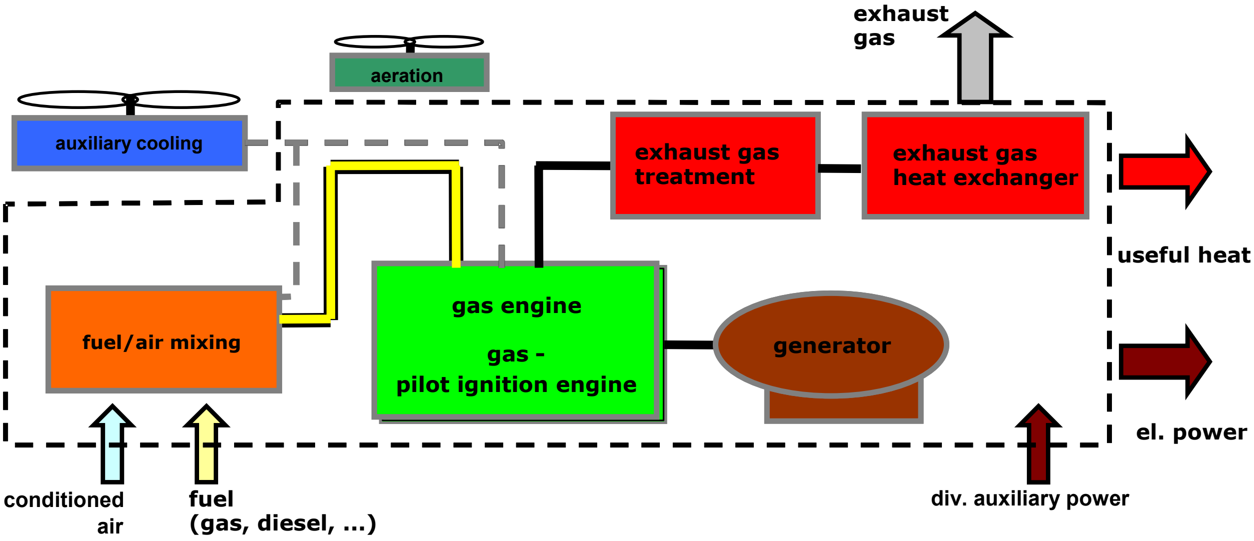


Figure 7-2: System elements of CHP plants

7.3 *Critical system components in the area of gas engine utilization*

Critical plant system components regarding gas utilization can by all means be deduced from operational experience up until now with CHP facilities operating on wood gas. From the perspective of engine manufacturers the problem areas presented in Figure 7-3 can be narrowed down that should be mastered through stringent precautionary and maintenance measures [55].
The carrying out of maintenance operations is in accordance with the respective CHP plant manufacturer and with his instructions. Because of the components of wood

gas (carbon monoxide, hydrocarbon compounds, etc.) the maintenance instructions of the CHP manufacturer must be strictly complied with.

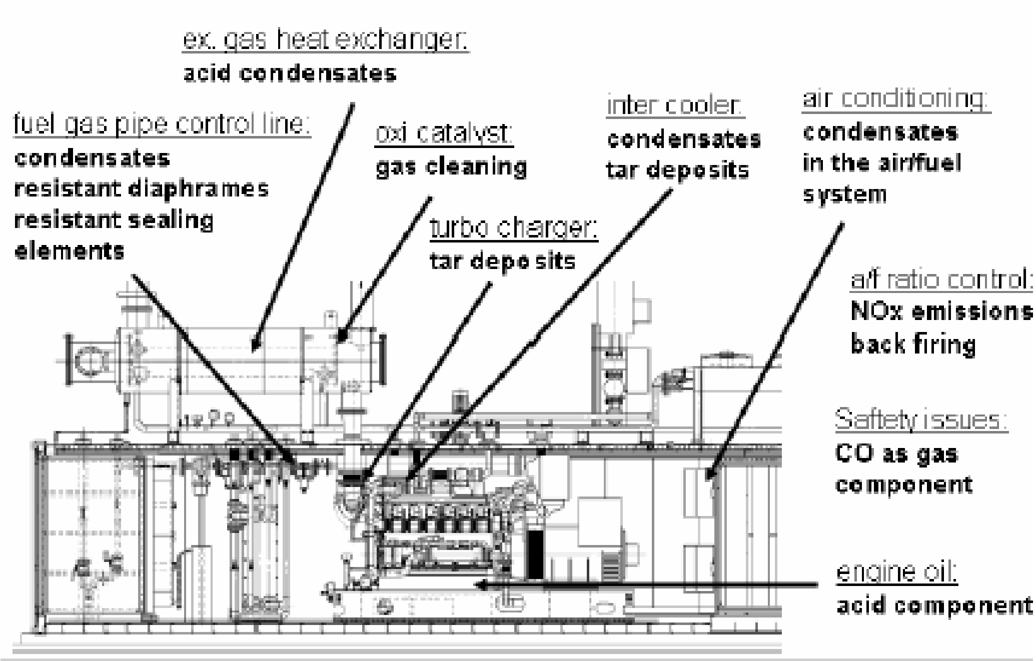


Figure 7-3: Critical plant system components when using wood gas in CHP plants with combustion engines [55]

In addition, attention is drawn urgently to the following points:

- explicit job instructions of the persons put in charge of the assignment.
- danger of suffocation and poisoning – inert gas blanketing (scavenging) of the plant, reliable combustion and disposal of the scavenging gases
- danger of fire and explosion – concentration monitoring (hand-held warning devices, stationary gas detection system)
- contamination with condensates from the plant – wearing of suitable protective clothing (gloves, safety goggles, etc.)
- protection from accidental start-up
- electrical safety measures

7.3.1 Technical construction of the gas control system

Chemical resistance of the materials used

The various manufacturers have optimized the quality of the membrane material in gas valves for natural gas. When using wood gas there is occasionally the accumulation of small amounts of aerosols or components condensed from the gas that causes the membrane material to swell. Figure 7-4 shows a membrane of the Spiez plant that indicated signs of chemical instability against producer gas impurities already after only a brief period of use.

This problem can be eliminated relatively easily through the suitable selection of the material – on the part of engine manufacturers this situation is felt to be unproblematic.

Figure 7-4: Swollen synthetic membrane in the gas control system of the Spiez plant [55]

Condensing of organic producer gas components

In the event of very large amounts of unremoved polycyclic aromatic hydrocarbons and cold components in the gas control system, the dew point is reached. This causes crystallization to take place. As a result, crystals from PAHs grow like dendrites in the component. In this case first the gas filter is blocked by the crystals and the engine shuts down due to “gas control system failure” – see Figure 7-5.
In the case of the Boizenburg plant (> 1g naphthene/Nm³) the first measure on the part of the customer was to remove the filter; as a result, the high amount of tarry compounds caused a malfunction of the pressure regulator. In the case at hand attention is drawn to the importance of choosing appropriate measures to reduce pollutants in the producer gas and checking of the gas cleaning function (also monitored at other analyzed plants).

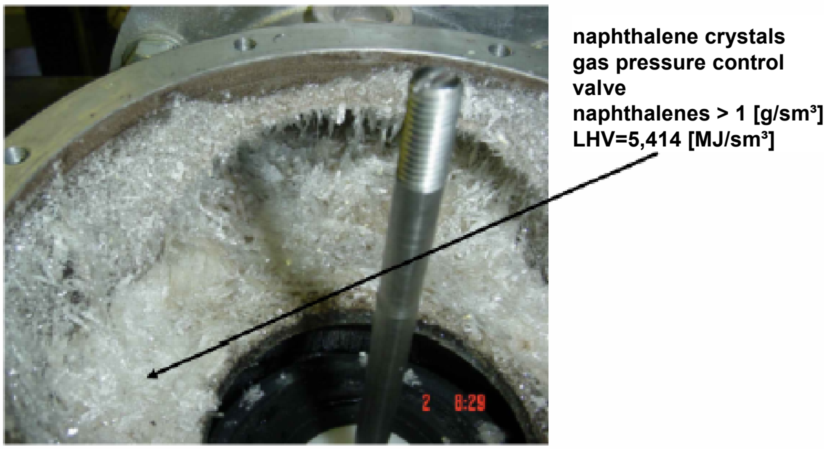


Figure 7-5: Accumulation of naphthalene crystals in the gas control system [55]

7.3.2 Impairment of the function of the exhaust gas turbocharger

With the aid of the turbocharger both the power density (specific costs of the engine) and the efficiency can be sustainably improved. With high charge pressures the temperature after the compressor rises to values around 200°C. The local high gas speed conditions as well as the pressure increase could cause separation of the solid/liquid particles suspended in the gas phase as well as condensation of gaseous mixture components. In this regard, Figure 7-6 provides a “look” into the diffuser housing of the turbocharger after 9000 operating hours and about 1000 hours after the increase in output in Güssing from 1750 kW to 1950 kW.
The corrective measure here is a moderate adjustment of the output of the engine, as well as improved gas and air filtration, respectively. Deposits of this type are also known from natural gas engines and cleaning is unproblematic (inclusion in the service interval).

Figure 7-6: Deposits of coke and tar components in the diffuser housing, [55]

7.3.3 Impairment of the function of the intercooler

Essentially, the same effect exists for the intercooler. Light tar components, which are gaseous in the gas due to partial pressure, can reach the dew point on the “cold” side of the intercooler with high charge pressures and a suitable adjustment of the temperature level. As a result, particles are also deposited on the condensate droplets, which then cause the intercooler, beginning with the outlet side, to become fouled with tarry deposits. Cleaning can be carried out only with difficulty, since the ribs of the intercooler can be easily damaged. Figure 7-7 shows this effect after the increase in output in Güssing after about 1000 operating hours.

To make the cleaning process easier, one suggestion is to change the concept of the intercooler. The same effect was observed at the Harboøre plant at about 9000 operating hours and must therefore be taken into consideration in the maintenance plan (cleaning interval). The intercooler in natural gas engines must also be cleaned after a specific number of operating hours – therefore no additional expense exists in dependence on the gas quality.

Figure 7-7: Clogging of the outlet side of the intercooler [55]

7.3.4 Pollution of the engine oil

The service life of the engine oil is closely connected with the impurities contained in the producer/fuel gas. These components get into the oil sump of the combustion engine through the contact of the pollutants with the piston liner of the cylinder wall and then through wetting of the oil lubricant. Oil maintenance is of great importance for the long service life of the engine. A quality parameter for the circulating engine oil is the TBN/TAN ratio, which is an indicator for the over-acidification of the lubricant in the engine.

In technical application, influencing of oil service periods is by means of a suitable additive. However, in this way only a minor effect can be attained. The majority of the measures must be implemented in the area of selection of the fuel, selection of the gasification system as well as gas cleaning. The oil service periods of the plants looked at, on the basis of experience, is from 300 to just less than 4000 operating hrs (Güssing).

Generally, checking the engine oil quality is possible by means of a visual examination of the oil sample (distinctive discoloration, typical odour) or an oil analysis. The oil analysis can also be drawn upon as an indicator of the quality of the gas generating and gas conditioning system. Each influence of a failure of the system or a change to another quality of wood (e.g. varying sulphur- or nitrogen content of the biomasses used) of the plant can be detected precisely. Figure 7-8 shows the first experience gained at the Emmenbrücke plant with a gas-Otto engine having sufficient periods of operation to provide meaningful data. The manufacturers and developers carried out the first catalytic converter tests at this plant. In this case the engine oil had been in use for a total of 350 hours (engine output about 60 kW_{el}). A conspicuous aspect at that time was the very high concentration of potassium (origin unclear); because of the high lead and copper values the first assumption was engine “sources” (stock material).

In the case of the Güssing plant relatively high ammonia values are contained in the wood gas. Negative effects of the ammonia were known from plants using natural gas in combination with refrigerating machines. The limit of the ammonia content in the gas was therefore specified at 55 mg/Nm³ (based on 10 kWh/Nm³). In the wood gas of the Güssing plant the ammonia values were more than 10-fold higher. As a result, in the operation of the Güssing plant special attention is also paid to how the ammonia in the wood gas affects the properties of the oil. To the surprise of all concerned, the effect was overestimated. According to the present state of knowledge, ammonia does not represent a problem regarding pollution of the engine oil when using wood gas (Note: As a result of internal engine combustion attention must be paid to the formation of fuel-NO_x).

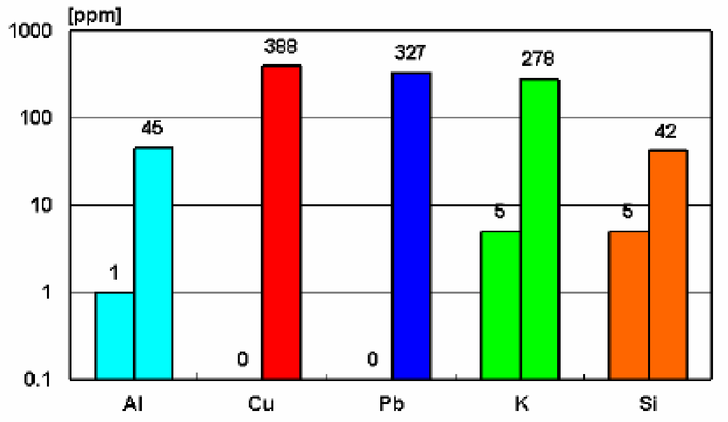


Figure 7-8: Oil analysis after 350 operating hours at the Emmenbrücke plant [55]

7.3.5 Deactivation of the oxidation catalytic converter

Deactivation of the oxidation catalytic converter can result through a condensate failure in connection with the incorrect positioning of the oxidation catalyst as well as due to wetting of the catalyst surfaces with alkali-, alkaline earth- and heavy metal compounds.

The loading of the producer gas with heavy metals has severe consequences on the decrease of the conversion rates due to the adsorbed catalyst poisons. In this regard, Figure 7-10 shows the measured decrease of the conversion rate.

On account of this effect elementary analyses of the surface layer were carried out at the plant of the oxidation catalyst manufacturer. These analyses – see Figure 7-1 – showed, in addition to the catalyst poisons lead and zinc, also potassium, which together with calcium causes a glazing of the active surface and is felt to be an important factor regarding the impairment of the secondary treatment of exhaust gas.

Figure 7-9: Functional impairment of the oxidation catalyst due to condensate failure [55]

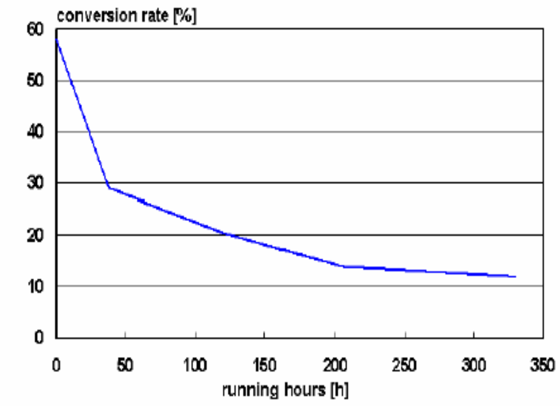


Figure 7-10: Decrease of the conversion rate of the oxidation catalyst of the Emmenbrücke plant [55]

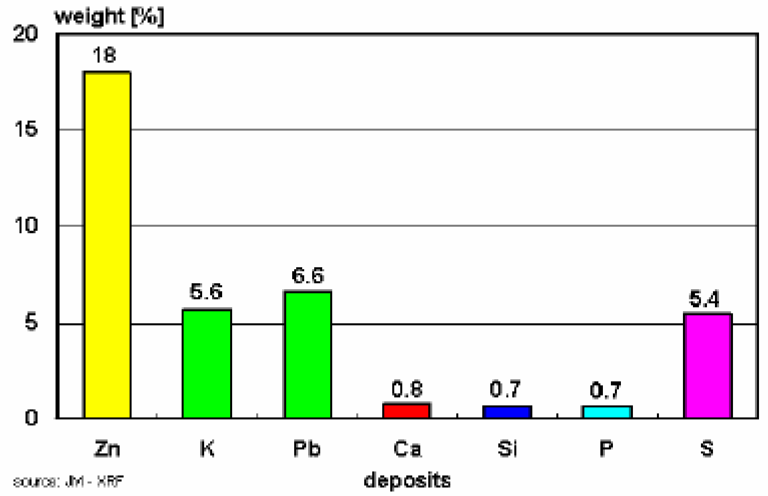


Figure 7-11: Elementary analysis of the surface layer of the catalytic converter [55]

This effect is the main cause of the short-term decrease of the conversion rates of the oxidation catalytic converter. The other elements (heavy metals) also contribute to the deactivation of the oxidation catalytic converter. Through the elementary analyses of the wood, i.e. the ashes, and the accumulating condensates it was possible to precisely determine the source material as the cause of these pollutants (Emmenbrücke plant). Essentially, this knowledge means that gas cleaning downstream from the gasifier must be able to remove these elements from the gas with high separation rates. Simple cleaning concepts, like a cork filter or only a scrubber on the basis of water as a scrubbing liquid, are insufficient according to the present state of knowledge. At the above-mentioned plants, where the catalytic converters malfunctioned after only a few operating hours, precisely these concepts were observed.

The achieved conversion rates in dependence on the service lifetimes presented in Figure 7-12 represent the current state in the development of catalytic converter systems in combination with the conformance/adaptation of the respective plant concepts (gas generation and gas cleaning).

In the meantime, research at several facilities have shown that the problem of removal of diverse catalyst poisons can very well be solved by several gas cleaning concepts. However, the operational reliability of the gas cleaning concept appeared decisive. Measurements at various plants showed that brief failures of the gas cleaning system can lead to drastic reductions of attainable conversion rates.

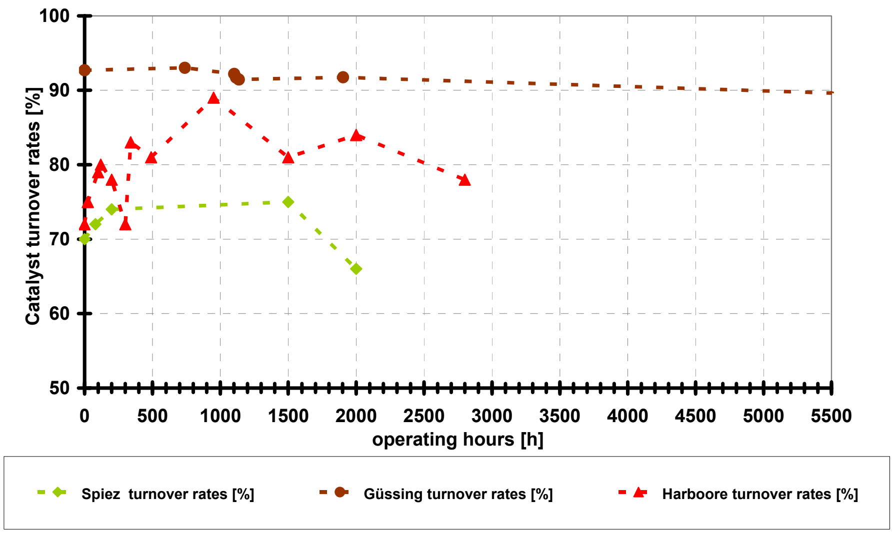


Figure 7-12: Catalytic converter conversion rates of selected wood gas plants, [55]

7.3.6 Operation of the exhaust gas heat carrier

The exhaust gas heat carrier is a plant component that reacts directly to bad gas quality because of the heating gas- (exhaust gas-) side contact. The load behavior and the load regulation in the heat distribution system are of extraordinary importance for the effects (heat exchanger – fouling, corrosion on the heat exchanger, etc.). In the case of load regulation control of the exhaust gas-side temperatures must ensure that the dew point never falls under the minimum level – what this means for the example of Harboøre is that due to the concentrations of pollutants, as for example sulphur dioxide (SO_2) or hydrochloric acid (HCl), the plant operator must pay attention to remaining as briefly as possible in an operational state with an accumulation of condensate, especially in stop-and-go operation and in a part load case.

7.3.7 Conditioning of engine cooling air and combustion air

Management of the cooling air and the intake air is very important for fault-free operation. This above all because the relative humidity and the temperature fluctuate in very broad ranges and in a system operating at “maximum” it can happen that an accumulation of condensate causes the dew point to fall below the minimum level due to overcooling the gas before the engine and in the gas control system, respectively.

7.3.8 Alternative systems of secondary treatment of exhaust gas

Besides the possibility of secondary exhaust gas treatment by means of an oxidation catalytic converter there is the potential solution of thermal post-oxidation (CL.AIR [55]) to reduce engine emissions. These systems are very reliable in operation also with gases of bad quality (catalyst poisons) and are already being used in more than 200 units in countries with strict CO and formaldehyde emissions.

Another approach to controlling CO emissions can be seen in the concept of the Civitas Nova plant. In this case the location of the gasifier was coupled with that of a biomass heating station. The exhaust gas of the engine is routed during full-load operation directly into the zone of the feed grate (high temperatures). The post-oxidation of very high raw CO engine emissions of 4630 mg/Nm³ can be reduced by the installed concept to a value of 6 mg/Nm³@ 3 % O_2. The total plant emissions with regard to released amounts of NO_x can be brought down to 240 mg/Nm³ by this applied gas utilization concept.
It must be considered that in this case boiler- and gasification operation are coupled; this has a reaction on the integration of the entire plant regarding heat as well as on the operation of the biomass gasification plant.

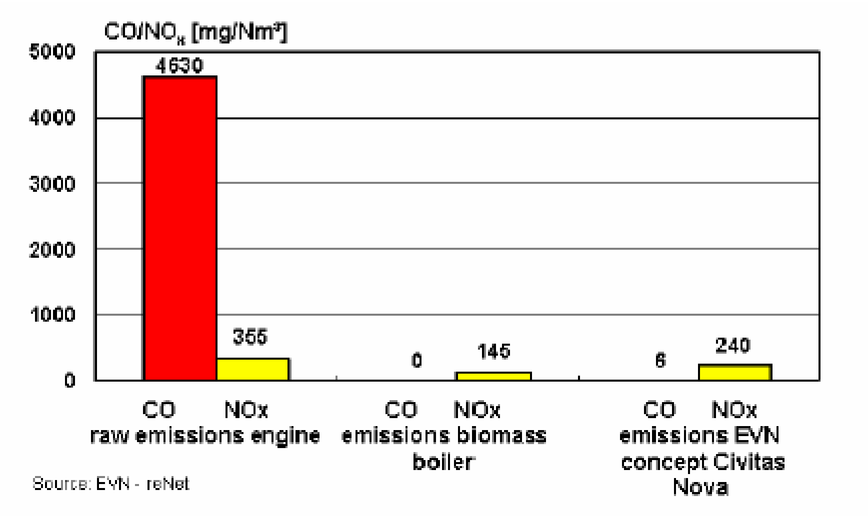


Figure 7-13: Concept-specific CO/NO_x emissions of the Civitas Nova plant – engine concepts with low potential (@3% O_2) [55]

7.4 *Operation of CHP plants – integration of energy*

CHP plants represent a concept for “decentralized energy supply” through which the energy (electrical energy and heat energy) required by the final consumer is to be provided from local energy centres – the basic idea behind this, is to transform locally available biomass in decentralized units to provide electrical power and heat.

With regard to this generated electrical energy, the operation of such CHP plants can be both network-bound and also independent (island operation). In the case of network-bound operation the produced electrical energy is fed into the supply grid of the local power supplier. The amount of heat generated as a by-product is normally transmitted over a local district heating system to the final consumers (see Figure 7-14).

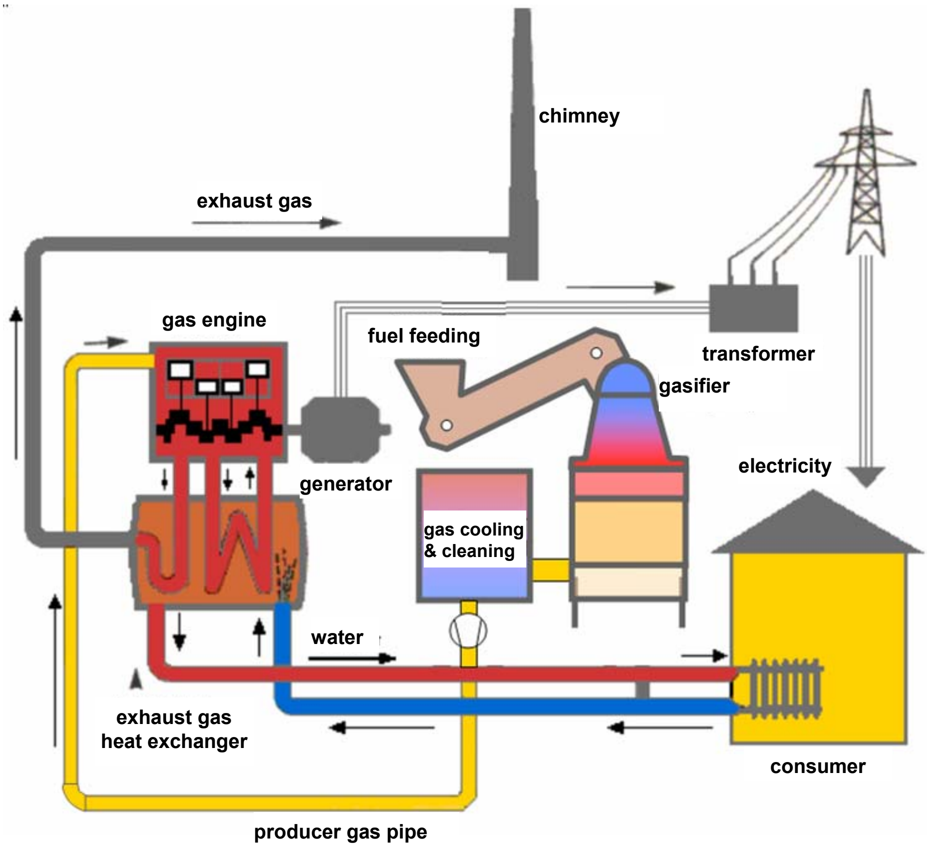


Figure 7-14: Classification of the energy of CHP plants based on biomass gasification in the local energy supply network

Regarding the classification of such plants, under the premises of decentralized provision of electrical energy and heat there are a number of points that should undergo closer examination.
The following points offer an overview of details to be heeded in the context of energy classification:

- integration in and connection to the district heating network,
- the size of the short- and long-distance district heating network,
- the heat demand characteristic of the heat purchasing network (amounts of heat purchased, load curve, etc.),
- integration in the local power grid,
- availability of the fuel (fuel logistics, fuel quantity, fuel quality),
- adaptation of the plant size to local operational conditions,
- base load classification of the CHP system for maximized overall energy efficiency [38],
- attainment of required primary energy savings in comparison to the reference values for separate production of power and heat [38].

Integration in the power grid must be undertaken in coordination with the local energy supply companies – a purchasing obligation and supply with application of the respectively guaranteed tariff schemes applies for certified green electricity plants through the legal framework of EIWOG (Austrian power management and organization law) and the green electricity law.

Heat energy can be transported only over limited distances and is therefore used mainly in short-distance district heating systems. For the commercial and economical operation of the whole plant a number of conditions must be fulfilled that are dependent on the actual plant size for the supply of heat and the structuring of the short- and long-distance heating network. For the attainment of a total efficiency criterion a heat-controlled plant is felt to be practical – this means that the heat energy requirement determines the production of the amounts of electrical energy. The heat energy requirement is determined by the size of the local heating network and it's supplied objects as well as by the seasonal heat purchasing characteristic – see Figure 7-15.

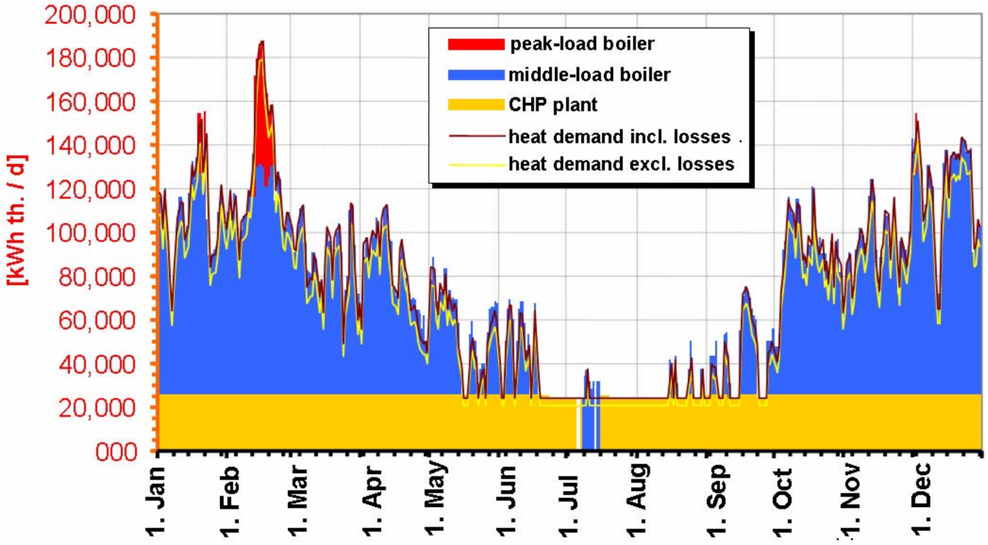


Figure 7-15: The yearly output curve of heat requirement in a long-distance district heating network – exemplary according to [56]

As can be seen in the Figure above, year-round operation necessitates consideration of the minimal heat requirement during the summer months and the heat requirement in the transition period due to the outside temperatures. The heating limit here represents a temperature limit that if not maintained, and depending on the construction of the respective building, necessitates added heat from the installed heating supply system to reach the desired room temperatures – there is no explicit heating requirement above the heating limit, but a heat requirement for water heating, provision of process heat, etc. The year-round heat requirement in the Figure above results through the required process heat and heat for provision of hot drinking water, which generally produces a constant load band.

When dimensioning room heating systems one generally proceeds on the basis of the maximal heating load on the coldest day of the year. Regarding the dimensioning of CHP components, the heating loads of the individual objects must be evaluated with simultaneity factors and the heat supplying devices classified on the basis of these values. Basically, the interrelationships of the heat purchasing characteristic are presented in the annual load duration curve diagram. In such diagrams the frequency (e.g. evaluated in hours per year) of the heat load is plotted over the year – see Figure 7-16.

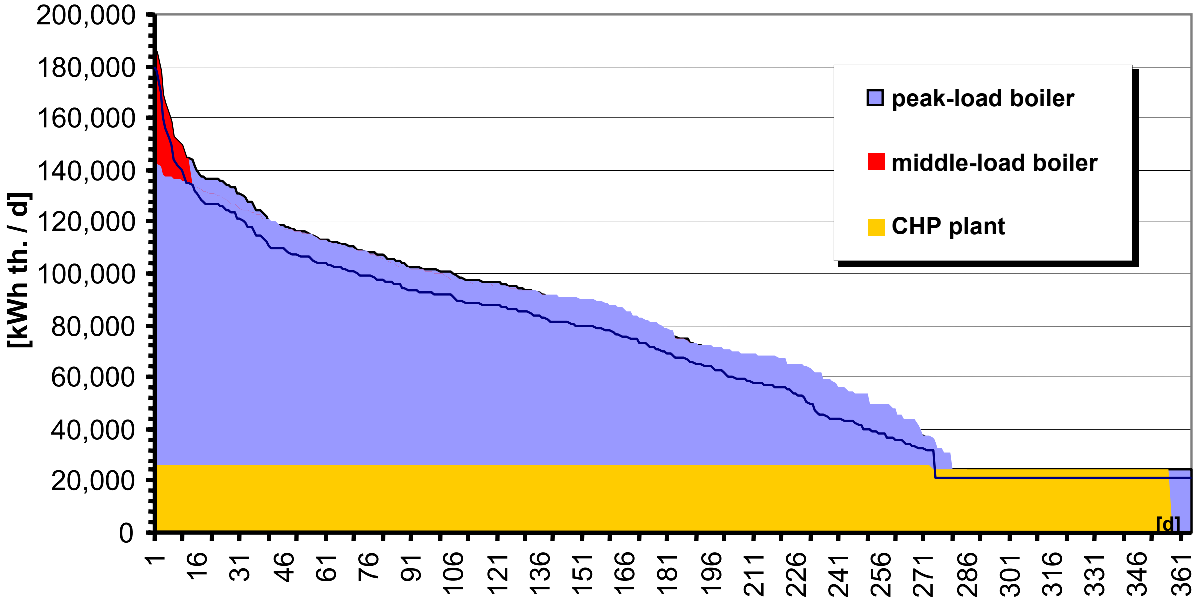


Figure 7-16: The annual load duration curve for the heat requirement of a long-distance district heating network – exemplary according to [56]

Regarding the integration of heat generating systems, there is the possibility of classification in base load, medium load and peak load units [57], [58]. If one assumes the trouble-free feeding of electrical energy, then cogeneration units are used preferably for the provision of base load heat. At the same time, a good level of plant utilization of the comparatively more cost-intensive cogeneration technology is attained over the entire year, since the heat requirement is ensured over a considerable period of the year through the constant purchase by the heat distribution network. As shown in Figure 7-16, the classification of base load plants in the range of, e.g., 10-15% of the maximal heat load of the heat distribution network. If one assumes a classification of the cogeneration plant in the example above of 10% of the rated load, then the yellow-highlighted area represents the base load energy requirement.

To cope with possible overcapacities of thermal energy, the following potential solutions, among others, are available:

- part load operation of the cogeneration plant (biomass gasification cogeneration possibly only little or no possibility of part load operation) - brown highlighted area
- increase of the heat loads in the summer months through replacement of the electrical loads with thermal processes (cooling of buildings through sorption-type refrigeration machines, equalization of load cycles through storage systems, avoidance of electrical systems for heating of water for drinking)

- modification of the heat purchasing characteristic (classification of the cogeneration plant in an interconnected thermal system with industrial- and process heat demand for drying processes, production processes with a process heat demand, biomass treatment plants, etc.)

The enumeration above represents the principal possibilities of the broadening of the band load in heating networks, which are determined on the basis of the heat purchasing characteristic of the individual consumers (e.g. housing developments). Carrying out of these measures is possibly connected with considerable expense. For this reason, the detailed examination of the load characteristic in advance is recommended.

In many cases auxiliary cooling systems (e.g. table coolers) are used that serve the purpose of emergency cooling and/or intermediate cooling in the event of a forced outage fluctuation of the heat distribution network and of a reliable shut-down of the plant. Operation with constant use of the auxiliary cooling system should not be the result of planning and dimensioning work, since under these conditions release of surplus thermal energy into the environment and achieving the total efficiency criterion of promotion requirements can be endangered. The definition of efficiency criteria with the commitment to the resource-conserving and efficiency-maximized operation of cogeneration plants is contained in various comprehensive bodies of legislation (exemplary), as can be seen in the following listing:

- Green Electricity Law – Official Bulletin I No. 149/2002
- Austrian Trade, Commerce and Industry Regulation Act 1994, Appendix 6 (§71a)
- Upper Austrian Power Management and Organization Law 2001:
- Directive 2004/8/EC of the European Parliament and the Council of 11 February 2004 concerning the promotion of CHP in the domestic energy market, [38]

In this context, the Green Energy Law defines the efficiency criterion [39] for the utilization of the combined product of electrical and thermal energy in cogeneration applications regarding the remuneration of the input of combined electrical and thermal energy. The promotion of the production of electrical energy from cogeneration technologies is possible only through the efficiency-maximized generation of the combined product (electrical and thermal energy) with infeeding into a public district heating network und the application of resource conserving and environmentally sound conversion technologies and energy sources. The efficiency criterion is defined as indicated in Equation 7-2 [39].

$$\frac{2}{3} * \frac{W}{B} + \frac{E}{B} \geq 0.6 \qquad \text{Equation 7-2}$$

W … amount of heat that is fed into the public district heating network [kWh]

B … total fuel utilization [kWh]

E … amount of energy that is fed into the public electricity network [kWh]

The Green Electricity Law stipulates the increase of the efficiency criterion up to **0.6** as of the **year 2005.** For the erection and operation of plants this means that their thermal classification is essential and represents an important basis for planning.
Concerning the resource conserving application of energy sources in Appendix 6, the Austrian Trade, Commerce and Industry Regulation Act of 2004 designates such an obligation, which is administered by the Trade Authority. The implementation of this regulation, but also of certain laws and regulations of Austrian states (e.g. Upper Austrian Power Management and Organization Law), recently draws more strongly on a directive of the European Union – Directive 2004/8/EC [38]on the promotion of cogeneration oriented on the effective heat demand within the domestic energy market.
Within the scope of evaluation of the eligibility for promotion of cogeneration plants, this directive earmarks criteria for energy-efficient operation in the sense of the state of the art that yield a primary energy savings of at least 10% in comparison to the reference values for separate generation of power and heat. The goal of this directive, among other things, is the promotion of renewable energies to reduce dependence on imports, promotion of regional energy acquisition, etc. as well as the examination of the eligibility for promotion of various cogeneration technologies. The scope of application of this directive is defined in the annex of the directive.

a) gas turbine with heat recovery (combined process)
b) back pressure turbine
c) extraction condensing steam turbine
d) gas turbine with heat recovery
e) internal combustion engine
f) micro-turbines
g) Stirling engines
h) fuel cells
i) steam engines
j) Rankine cycle with organic fluid
k) any other technology or combination of technologies for which the definition: “cogeneration” applies as the simultaneous generation of thermal energy and electrical and/or mechanical energy in a process

The directive is to be implemented corresponding to the implicit conformity of cogeneration technology on the basis of biomass gasification to point k) in the listing above. Conditional upon the obligation of the plant to fulfill a yearly total degree of utilization, the stipulations of this directive can be achieved only by adhering to planning specifications, e.g. the strict base load classification of the plant taking into account the part load behavior, heat purchasing characteristic of the short- or long-distance district heating network, heat-controlled operation, etc.

7.5 Concepts for reducing pollution in CHP plants

The following listing represents possibilities already put into practice for reduction of pollutants in the exhaust gases of gas engine CHP facilities. The spectrum of applied methods ranges from use in the automotive branch to that of stationary engines. Attention can be drawn in particular to the restrictions of the effectiveness of the enumerated measures in interaction with the marginal conditions concerning the use of wood gas (see 7.3).

7.5.1 Introduction

The measures for prevention of pollutant emissions from CHP plants are subdivided into primary and secondary measures. The primary measures aim at influencing the internal engine combustion process. This can be accomplished, for example, by exhaust gas recirculation (EGR), water injection or lean-burn operation. The secondary measures provide for secondary treatment of the resulting exhaust gases after the combustion process – here mainly catalytic converter systems are used.

As a rule, pollution limits cannot be reached with only individual, i.e. isolated, technical measures. As a result, concept solutions already in practice avail themselves of a combination of primary and secondary measures. The following combinations are used most frequently [52], [53], [54].

- a three-way catalytic converter with Lambda-1 operation
- the lean-burn engine concept with an oxidation catalytic converter (oxi-cat)
- the SCR process (selective catalytic reduction) with an upstream oxi-cat
- soot particle separating filter (in diesel engines)

The applicability of the possible combined concepts depends strongly on the kind of fuel used – see Table 7-4.

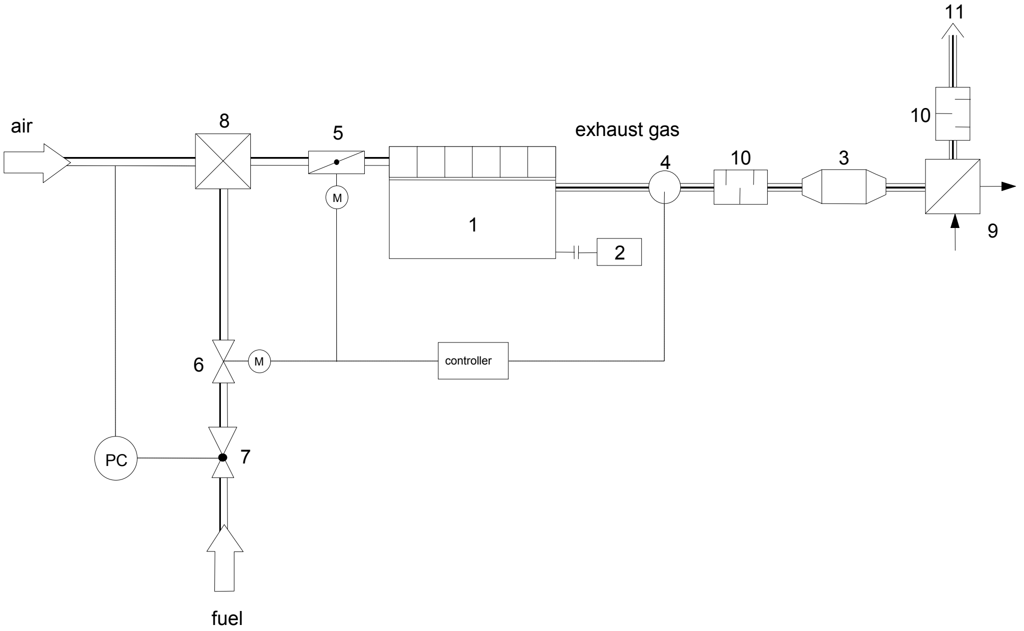
Table 7-4: Overview of engine concepts in combination with exhaust gas cleaning

Engine type	**System of secondary exhaust gas treatment**	**Fuels used**
gas-Otto engine Lambda=1	3-way catalytic converter	natural gas liq. petroleum gas
gas-Otto engine lean-burn concept	oxidation catalytic converters	natural gas liq. petroleum gas landfill gas sewer gas biogas wood gas
gas-Diesel engine pilot injection concept	SCR process with oxidation catalytic converter in certain cases also with a soot filter)	diesel/heating oil natural gas liq. petroleum gas landfill gas sewer gas bio gas wood gas

Secondary exhaust gas treatment systems used in wood gas operated CHP plants have come up against physical limits. Loading with undesirable wood gas components leads to deactivation of the catalytic converter system [52], [53], [54].

7.5.2 The three-way catalytic converter

The three-way catalytic converter pre-requires stoichiometric combustion in internal engine combustion (λ=1). The arising exhaust gases are conducted through a platinum/rhodium catalytic converter, which functions optimally in the temperature range of 400-600°C.



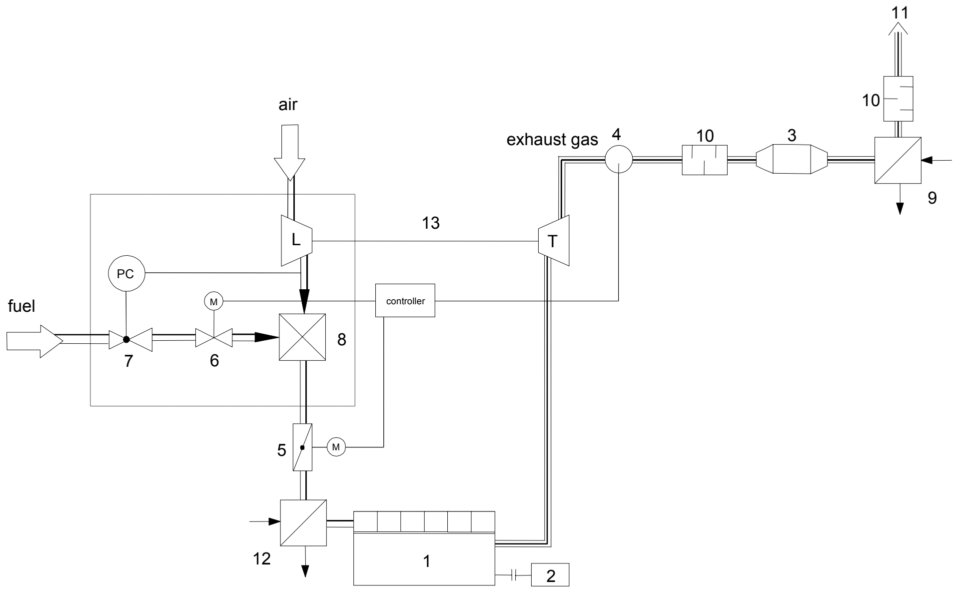
1	Engine	7	Pressure regulator
2	Generator	8	Gas/air mixer
3	Catalytic converter	9	Exhaust gas heat exchanger
4	Lambda probe	10	Sound absorber
5	Butterfly valve	11	Chimney
6	Gas valve		

Figure 7-17: Functional scheme of a 3-way catalytic converter [52]

In the 3-way catalytic converter nitrogen oxides, carbon monoxide and hydrocarbons are suitably converted in stages. The catalyst coating brings about this conversion very effectively – the prerequisite for this is conducting internal engine combustion with a very narrow Lambda window. The reason for this is that too much excess air would only promote the oxidation of unburned producer gas components, but would not allow the reduction of nitrogen oxides. The 3-way catalytic converter cannot be operated in diesel-, gas/diesel- and 2-stroke engines due to the excess air ratios.

7.5.3 The lean-burn engine concept

With the lean-burn engine concept (see Figure 7-18) internal engine combustion is capable of air excess ratios of 1.45-1.6. The resultant low flame temperatures do not lead to the formation of thermal nitrogen oxide compounds and thus it is possible to remain below the prescribed emission limit values. A disadvantage of this concept is the higher CO emissions, which entail the use of oxidation catalytic converters.



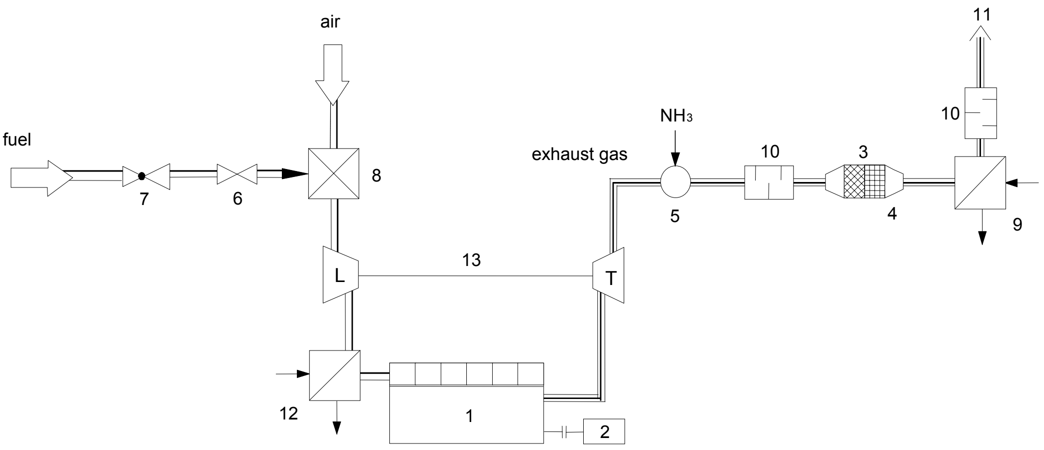
1	Engine	8	Gas/air mixer
2	Generator	9	Exhaust gas heat exchanger
3	Oxidation catalytic converter	10	Sound absorber
4	Lambda probe	11	Chimney
5	Butterfly valve	12	Intercooler
6	Gas valve	13	Turbocharger
7	Pressure regulator		

Figure 7-18: The control scheme of a turbocharged gas-Otto engine functioning according to the lean-burn concept [52]

Judging from the current state of development, a great deal of experience has been gained through the application of this concept in the utilization of special gases; it has proved to be a practical system that allows compliance with emission limit values so long as technical restraints are observed (gas purity, reduction of catalyst poisons, condensate- and dust-free exhaust gases).

7.5.4 The SCR process

The SCR process (selective catalyst reduction) is applied where the manner of construction does not allow the 3-way catalytic converter to be used with Lambda-1 control and the lean-burn concept. The SCR process utilizes an ammonia catalytic converter and an oxidation catalytic converter. For the selective reduction of the nitrogen oxides ammonia (infeeding of pure substances or the injection of an ammonia/water mixture) is sprayed in. An oxi-cat is located downstream for the reduction of the ammonia and carbon monoxide emissions (see Figure 7-19).



1	Engine	8	Gas/air mixer
2	Generator	9	Exhaust gas heat exchanger
3	NH_3 catalytic converter	10	Sound absorber
4	Oxidation catalytic converter	11	Chimney
5	NH_3 dosing	12	Intercooler
6	Gas valve	13	Turbocharger
7	Pressure regulator		

Figure 7-19: Functional scheme of the SCR process [52]

Selective catalytic reduction necessitates very high apparatus costs and causes further expense during operation due to the constant consumption of ammonia. As a rule, this system is employed for diesel- and gas-diesel ignition spray engines – an upstream particle filter is used depending on the smoke number of the engine.

8 Summary

The overview of the technologies for biomass gasification represents a basis for the considerations, analyses and structuring of the document. The compiled stock of data forms the basis for the evaluation of the state of technical sciences regarding the current status of development of the planning, erection and operation of biomass gasification plants in combination with internal combustion engines on the basis of available citations and pertinent reports on experience gained.

The great number of presently existing variants of gasification technologies are based on fundamental principles described in the document – within the complexity of different gasification processes usually the basic type of process can be deduced, from which the plant system can be classified with regard to the requirements of the following process chain (gas cooling, gas cleaning, gas utilization) essentially on the basis of expected gas qualities, process parameters, parameters concerning safety engineering, plant emissions, etc. The various processes are classified and differentiated with regard to the parameters (output ranges, fuels, crude gas quality). Due to the reducibility of the fundamental process-specific schemes this document does not go into modified types of gasification.

The conditioning of crude gases from gasification reactors has to guarantee constant qualities of crude gas regarding dust-, tar-, condensate- and trace element load for subsequent gas utilization. The respective functionally efficient and fault-free process of gas cleaning determines the technical availability of the entire plant (contamination and fouling of plant system components, fittings and safety components, service lifetimes of the CHP exhaust gas oxidation catalytic converters, etc.). The area of conditioning includes process gas cooling, gas cleaning (de-dusting, treatment of tar and trace elements) as well as the treatment of residues and water.

The highest demands are made on the utilization of the producer gas from biomass gasification plants to be able to ensure the supply of electrical and thermal energy while reliably fulfilling criteria regarding stability, efficiency and emissions. The information given above includes the overview of functional concepts and system elements of CHP plants and explanations regarding the special gas application of wood gas combined with the summary of reports on experience gained in presently installed facilities. In terms of the current state of development, the technology of application of special gases has established itself, but requires adherence to marginal conditions such as engine control, maintenance of certain qualities of fuel gas to ensure fault-free operation of the gas control/safety- and mixing system, of the internal combustion process and secondary treatment of exhaust gas with, e.g. oxidation catalytic converters.

Gas and diesel pilot ignition engines are presently used as engine operation concepts; here the gas-Otto engine principle causes comparatively less expense for secondary exhaust gas treatment as well as comparatively lower emissions. The utilization of the combined product of electrical and thermal energy must be regarded as being compulsorily in connection with the utilization of gas in CHP plants. Due to foreseeable changes regarding promotion criteria for green electricity CHP plants with the fulfillment of efficiency criteria, the load classification of entire plants (heat-controlled plants, base load classification, part load capacity of the plants, etc.) is particularly relevant.

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