Mop Fan and Electrofilter: an Innovative Approach for Cleaning Product Gases from Biomass Gasification

Final project report

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Preface

This report summarizes the work which was carried out between April 2008 and September / November 2010 within the ERA-NET bioenergy project “Mop fan and electrofilter: an innovative approach for cleaning product gases from biomass gasification”. For this project a consortium was formed with the partners:

- TU Berlin, Institute of Energy Engineering, Chair EVUR (Germany)
- Beth Filtration GmbH (Germany)
- ERK Eckrohrkessel GmbH (Germany, subcontractor) and
- The University of Nottingham, School of the built Environment (United Kingdom).

Besides these partners the company La Mont-Kessel GmbH & Co. KG (Germany) which was involved in the design and production process of the heat exchangers from ERK has to be mentioned.

The project was sponsored by the national research agencies FNR (Germany) and EPSRC (United Kingdom). The project funding was subdivided into three parts by FNR: FKZ: 22018407 (TUB / ERK) and FKZ: 22018507 (Beth Filtration GmbH) and by EPSRC: EP/F038070/1 (University of Nottingham).

Content

1 Introduction

Thermochemical conversion of solid cabonaceous fuels such as biomass, peat, coal or different kinds of organic residues (wastes) by pyrolysis, smouldering combustion or gasification yield hydrocarbon substances in molecular structures from gaseous methane up to solid carbon structures like soot or char. Especially the vapour fraction of these intermediate to high temperature conversion processes defines the task for process engineers since the vapours will condense when the product gases are cooled.
Where in pyrolysis applications the condensed vapours form the desired liquid product in gasification they are the challenge in gas cleaning for engineers over decades. The success of gasification technology which delivers many future opportunities in carbon neutral supply of energy in forms of electricity, heat or chemicals from biomass depends to a large degree on successful working and economic gas cleaning technologies. Especially tar remains a problem for small and medium scale plants.
Tar was most often defined from practical issues of dealing with it. Milne et al. [Mil/1998] stated: "The organics produced under thermal or partial-oxidation regimes (gasification) of any organic material are called "tars" and are generally assumed to be largely aromatic". In the tar guideline [Nee/1999] tar is defined as: "Generic (unspecific) term for entity of all organic compounds present in the producer gas excluding gaseous hydrocarbons (C1 through C6). Benzene is not included in tar."
However, in newly examined applications using gasifier gases in fuel cells or as syngases for catalytic applications also the effects of "non-condensibles" such as ethylene, cyclopentadiene, and benzene can play a substantial role.

The project "Mop fan and electrofilter: an innovative approach for cleaning product gases from biomass gasification" was set up to combine new technological aspects to an adaptable gas cleaning concept gasification plants up to medium size with a few MW thermal power. In this class of plants the specific investment cost for gas cleaning are high and therefore solutions with low initial investments are preferred. Many plant operators who started up plants in the past two decades faced enormous operational and economic problems related to tar.

1.1 Principal considerations for separating tar from gasification product gases

Product gases that leave a downdraft or co-current moving bed reactor (often referred to as fixed bed reactor) or of fluidized bed reactor have temperatures in the range of 700 - 900°C. Some of this heat can be recovered by gas coolers. In most gasification plants gas is cooled to about 400°C to prevent condensation of tar.
In a subsequent step particles are removed with cyclones, hot gas-filters or baghouse filters, where especially the latter are limited in their maximum operating temperature.
The follow-up gas cleaning step in many pants is a kind of tar removal device which could work on a "dry" basis where the gas is lead over absorbent materials and further cooled. The intention is to transfer tar substances from the gas to solid surfaces.
More effective seems gas washing with liquid substances where the gas is cooled by evaporative cooling and washed by intensive contact of gas and washing medium in "gas washers / scrubbers" or washing columns. The problem here is the generation of contaminated liquids which have to be treated or disposed at additional costs. The use of organic liquid media was proposed in the last years in order to allow the combustion of liquid and contaminants preferably within the process.
Most interesting seems the use of catalysts to reform tar into non-condensible hydrocarbon gases to maintain the chemical energy of the tar and add this to the final heating value of the gas. Even though intensive research was carried out, no smaller commercial plant is incorporating such kind of technology up to date.

The aim of this project was to combine new as well as proven technologies for product gas cleaning of gasification product gas with the main intention for utilization of the gases in combined power plant units. It was not considered to put the requirements for synthesis gas production on scope as well.

1.2 Use of electrostatic precipitators (ESP) for tar removal

Electrostatic precipitators have been used for tar and tar aerosol separation for long time but also long time ago. There has been experience and knowledge within the coal gasification technology. The usage of electrostatic separation mechanisms first applied by Cottrell was soon made available. The systems offered by Siemens-Lurgi-Cottrell were readily available and in use for coal processing units. In coking plants ESP's remained up to date.
When considering their use in biomass gasification the installations in Harboøre (Denmark), Wiener Neustadt (Austria) or the use within research or in the OLGA gas cleaning plants developed by ECN and commercialized by Dahlmann have to be mentioned. Here filter systems from project partner BETH are in use.
One goal within the project was to test the separation efficiency for the different tar compounds from the gas and make use of this knowledge to design less complex but still efficient and cost effective working gas cleaning units.

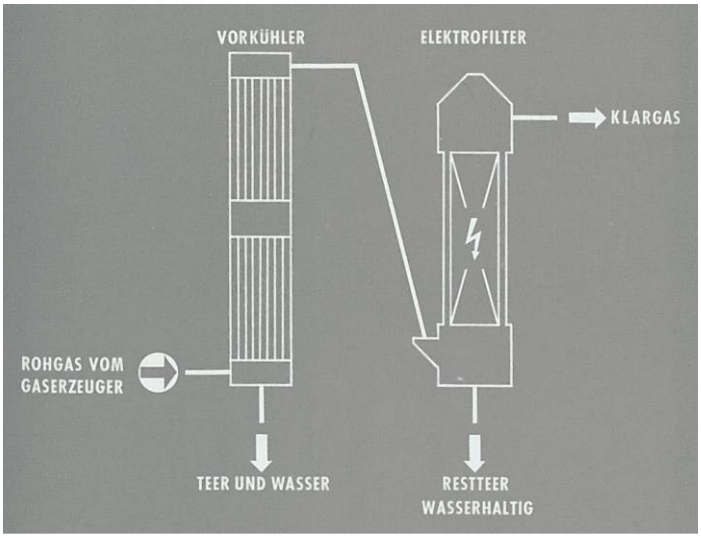


Figure 1.1 Use of cooler/ESP combination for separation of heavy tars from hard coal gasification [Ano/1960]

Figure 1.2. Example of ESP tar separator by Lurgi [Ano/1960]

Figures 1.1 and 1.3 show example configurations of industrial solutions for tar removal from product gases generated in coal gasification. Figure 1 is a setup intended for tar from gasification of hard coal whereas the scheme in Figure 3 provides a setup for cleaning product gases from thermal conversion of lignitic coal. The latter is more comparable to biomass gasification since both biomass as well as lignite have higher contents of volatile components than hard coals. Figure 2 shows a realized setup of ESP's for the abovementioned applications. Figure 3 shows some similarities to the OLGA-Gas cleaning-System [Kön/2007]. Heavy and lighter tars are removed separately at different temperature levels. Unlike OLGA where especially dewpoints of tar and water phase are strongly obeyed and the organic and anorganic liquids are kept apart, here heavy tar is quenched with water and then the tar is separated from the gas flow. In the comparably smaller biomass installations specific costs for disposal of the contaminated liquid phases are high. A separate upgrading of the residues into sellable products is most often not feasible.

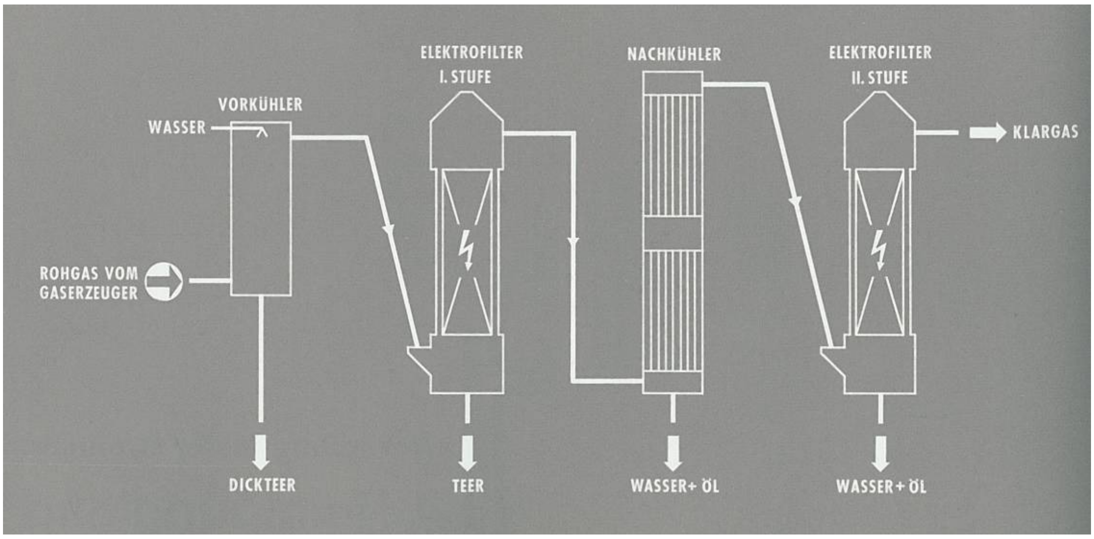


Figure 1.3: Combination cooler/washer/ESP for separation of tar from lignite gasification [Ano/1960].

An early comparison between gas washer and wet ESP was given by Seidenschnur and Groh in 1928 [Sei/1928]. They published tar separation efficiencies of 95,3% for a centrifugal washer by Theisen and 99,4% for removal by wet electrostatic precipitation. The voltage applied is given as 47.000 V at a current of 26 mA.

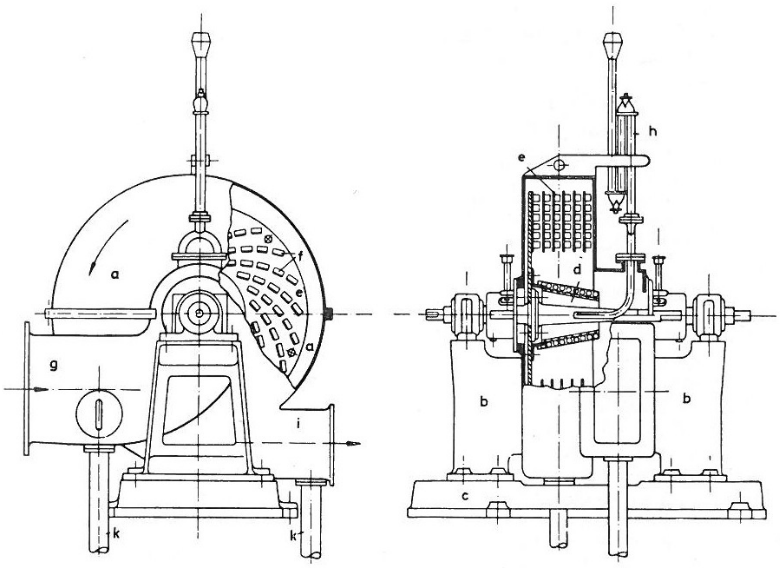


Figure 1.4: Theisen Washer [Kog/1964]

The Theisen washer was already patented in 1909 and was successfully used in multiple installations. This shows that washers with rotating internals can be considered for solving tar related gas cleaning tasks. Into this field falls the examination of the newly developed Mop-Fan where other internals are applied.

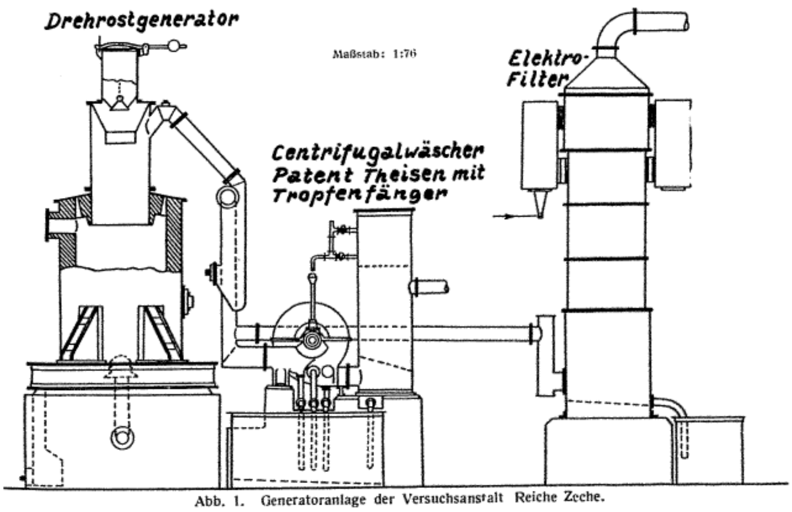


Figure 1.5: Gasifier teststand in Freiberg 1928 with centrifugal fan separator and ESP [Sei/1928]

Van Paasen et al. [vPa/2004] published 2004 a parametric study of tar separation efficiencies for removal of biomass gasification tar with ESP. It was shown that tar aerosols can be removed at high levels and their results are in good agreement with the older mentioned literature. Anyhow it was observed that the lighter hydrocarbons with significant vapour pressures are not very well affected or significantly removed by the application of the electric field. They remain as steam and will not likely form aerosols or condense/dissolve in the aerosols being present in the gas. Results from this project will be given in section 5.

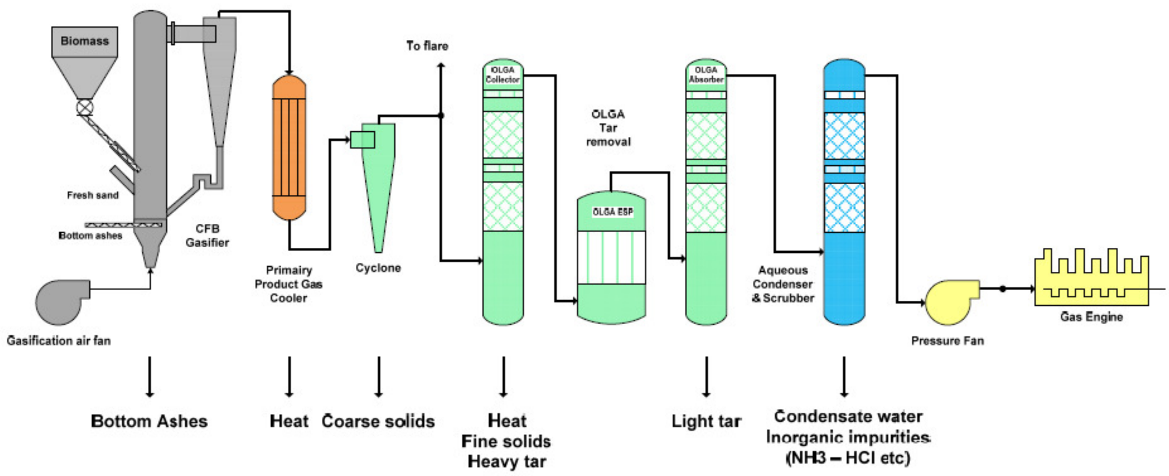


Figure 1.6: OLGA Gas Cleaning process (ECN and Dahlman) [Kön/2007]

2 The Project

In the EMF-project, the three partners Technische Universität Berlin (TUB), University of Nottingham (UNOTT), and Beth Filtration GmbH (Beth; or former Aerob Beth Filtration GmbH - ABF) and the subcontractor ERK Eckrohrkessel GmbH (ERK) will jointly investigate, develop and evaluate a modular and adaptable product gas cleaning concept which consists of innovative and proven gas cleaning technologies, namely the mop fan and the electrostatic precipitator. The major objectives are:

- To investigate the performance of the mop fan with respect to the removal of particles, ammonia and additional water soluble gas contaminants by adapting the design of the mop fan to the application of cleaning of product gases from biomass fluidized bed gasifiers
- To investigate the sensitivity of an electrostatic precipitator (ESP) with respect to separation of different tar components from the product gas and to improve the design and possibly reduce investment costs of ESP.
- To explore the combination of mop fan and ESP for better product gas cleaning.
- To optimise the designs of mop fan and ESP so that they can be used to produce clean product gas suitable for direct application in internal combustion engines etc.
- To design and test high-efficiency compact heat exchangers with structured surface tubes for gas cooling to increase the overall efficiency of the gas cleaning concept.

The proposed project has the following innovative features:

(a) For the first time the concept of the mop fan will be applied to the cleaning of gasification product gas.

(b) For the first time characterisation of an ESP in terms of sensitivity of tar separation for different tar components is to be experimentally investigated.

(c) The combination of mop fan and ESP is a new concept of product gas cleaning technology and has great potentials in removing fine particles, tars and chemical contaminants.

(d) The high-efficiency compact heat exchangers with structured surface tubes are used for cooling of product gas for the first time.

The following scheme in Figure 2.1 gives an overview about the fields in the project covered by the individual project partners. TUB operates a fluidized bed gasifier and provides gas and tar analysis methods for research in the project. ERK Eckrohrkessel GmbH designed and manufactured 4 heat exchangers to be tested in the plant. They were positioned directly on top of the gasifier. Beth filtration designed, built and set up quench and ESP-system and the necessary supplies. UNOTT designed manufactured and tested the mop-fan, which is a centrifugal fan system which acts as gas washer. All systems were put together at the end of the project at TUB for system tests.

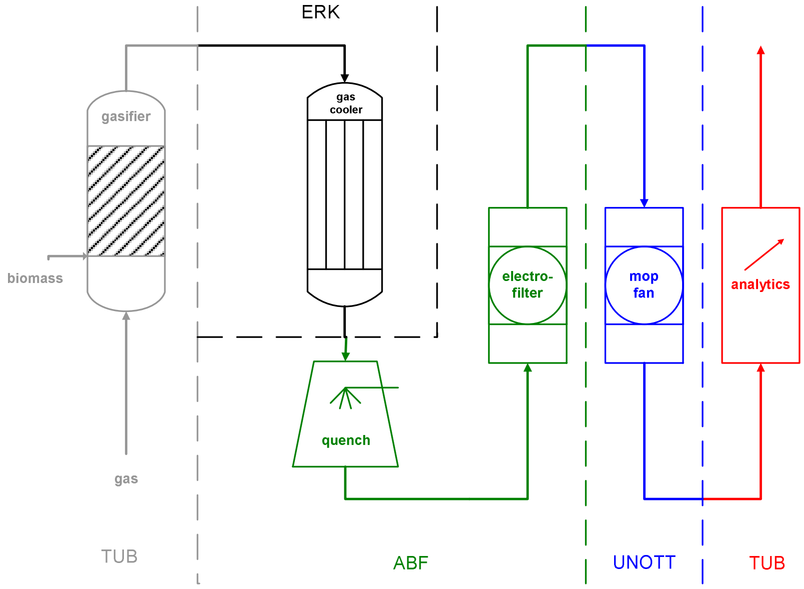


Figure 2.1: Scheme of plant flow sheet and responsibilities of the project partners

3 TUB – Fluidized bed gasification pilot plant and analysis

3.1 Design basis and Experimental Conditions

Design and operation of the experimental fluidized-bed gasifier were determined by design conditions and experimental results of a previous lab scale fluidized-bed gasifier made of quartz glass. Basic setup consisted of fluidized-bed gasifier with two freeboard segments (manufactured of heat resistant steel material 1.4841 and designed for an operating temperature up to 1.100℃), hot gas filter (HGF), gas burner and hot gas fan. This basic system was then further equipped with quench and ESP and mop-fan. For safety reasons an overpressure release is added to the system.

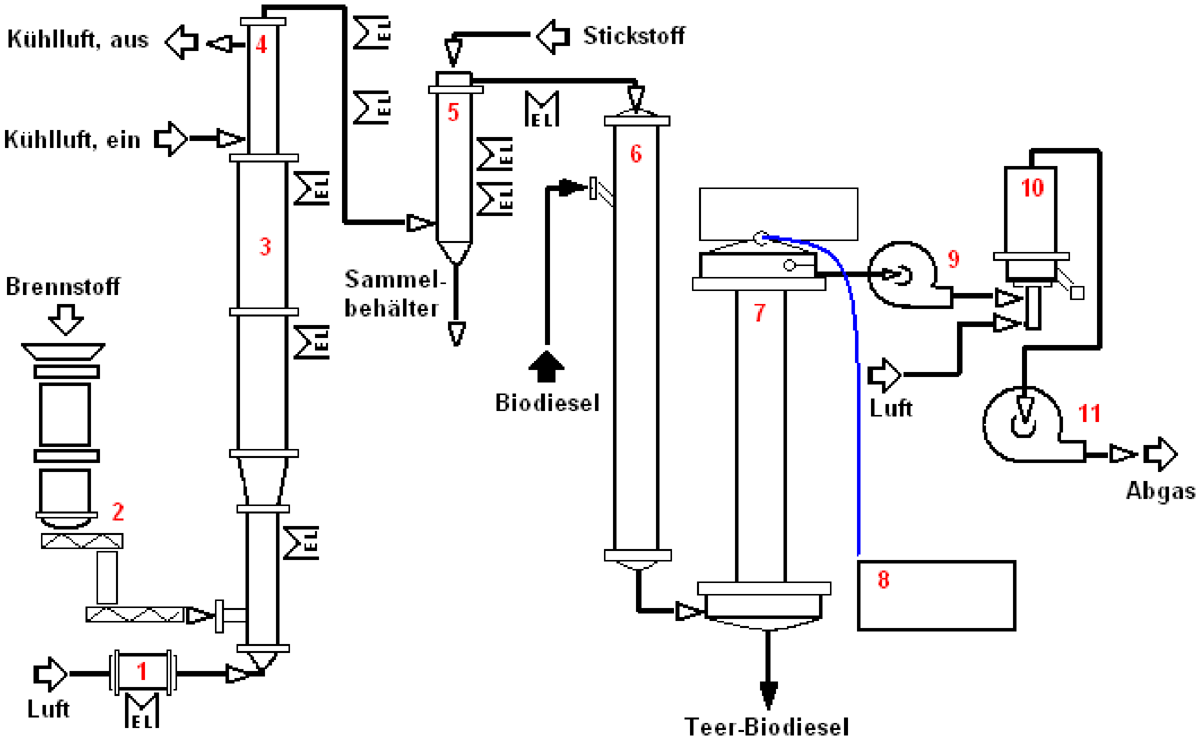


Figure 3.1:Systematic setup of TUB gasification plant and positioning of downstream equipment

The systematic configuration of the TUB plant is shown in Figure 3.1. Number 1 is the feed of gasification agent (air) and its preheating unit. Fuel hoppers and inlet screw for reactor feeding are depicted as number 2. Number 3 in the drawing is the bubbling fluidized bed reactor. Following the gas path further the heat exchanger (4) and the hot gas filter (5) for dust removal follow. Quench (6) and ESP (7) together with the high voltage supply (8) are positioned before the Mop-Fan (9) in the system. The final components are gas burner (10) and hot gas fan (11) In Figure 3.2 two views on the realized plant are shown. It was in configuration I at the time the pictures were taken.

Parametric studies were performed in three configurations:

I) Basic setup,
II) Basic setup with heat exchanger,
III) Basic setup with/without heat exchanger, quench and electrostatic precipitator (located between hot gas filter and gas burner) and
IV) Complete setup with heat exchanger, hot gas filter, quench ESP and mop fan.

The basic setup is the gasifier with feeds of fuel and gasifying agent hot gas filter and burner. Instead of the heat exchanger a blank tube can be installed.

Before operation of one of the experimental configurations surfaces of the entire equipment are heated with of electrical heating elements. For this purpose heating tapes, heating cables and heating mats with operation voltage of 230 V or 400 V are used. A self-designed switch cabinet with 14 control circuits is used for temperature control. Installed power of heating elements is between 0.1 kW for short pipe segments or pilot filter and up to 2.5 kW for reactor segments like hot gas filter. To reduce heat loss of heated plant unit's thermal insulation was required. As insulation material isoTHERM S (Frenzelit) with a layer thickness of 25 mm and an application limit of 1.100 °C is used. To ensure outer surface temperatures below 50°C at minimum two layers of the material are required.
One the one hand requirement of heating up is to ensure surface temperatures above 400°C to prevent tar condensation, on the other hand to reach a minimum system temperature throughout the experimental plant setup before start-up of each experimental run. Fluidized bed gasifier and the two freeboard sections are heated up to an outer surface temperature (measured and logged with five thermocouples) between 600°C and 800°C, hot gas filter and pipes are heated up to 400°C. The maximum allowed inlet gas-temperature of the hot gas fan located behind the gas burner of about 200°C required special designed cooling devices. To ensure a gas temperature under maximum operation temperature of hot gas fan gas cooling is performed by an indirect two stage water cooling unit and a direct cooling unit designed as water spray nozzle, located between gas burner and hot gas fan. Quench and electrostatic precipitator are designed for operation without heating devices or thermal insulation.

a)  b) 

Figure 3.2: Photographs of TUB gasification plant in configuration I

3.2 Operation conditions of Gasification test plant at TU Berlin

In this section the operation of the TUB pilot plant is described and measured values of operational parameters are presented. In the following chapters about the examined downstream components additional data will be presented which also originated from this plant except for the measurements in combination with the Mop-Fan at UNOTT.

3.2.1 Start-up and shut-down of the plant

The plant is operated with char as reactive bed material. For startup the entire system is purged with preheated nitrogen (N_2) to ensure absence of oxygen (O_2) to prevent mass loss of char before actual operation as well as protecting against explosion or blow ups. Purging with preheated nitrogen is also used to achieve tar free measurement pipes connected with online gas analysis equipment like GC/MS and FTIR before and after each measurement run. In the main experiments gasification is performed with pressurized air as gasifying agent. This air is dried after compression and has a water dew point of 7°C. The change from nitrogen to air is initialized if the gas temperature of the fluidized-bed is above 300°C and the two freeboards are preheated to at least 600°C. Special care has to be taken about the hot gas filter so that no tar condensation will occur in the ceramic filter tubes. To ensure a steady state of gas and surface temperatures of the plant a preheating start-up phase of around 2 hours is required. To reach very stable system conditions another 2 hours on stream are recommendable.
Shut-down procedure of the plant consists of flushing the plant and measurement devices with nitrogen to ensure that the pipes and vessels are free of explosive product gas and condensable tars. Furthermore the char bed is supposed to remain present. Before switching off the heating devices, the hot gas filter is cleaned via back-pulsing with preheated nitrogen to prevent blocking of the ceramic filter candles with tar and particles. Purge of HGF is started after shut-down of the plant. To prevent pressure sensitive devices like pressure sensors and measurement instruments (GC/MS, FT-IR) from over pressure measurement tubes are disconnected before HGF back pulsing.

3.2.2 Fuel Properties

The fuel used in the project was milled wood chip from a saw mill in Milmersdorf (Brandenburg). The wood processed there is coniferous wood mainly pine, spruce and sometimes larch. Pine is the dominating wood and it is the wood used in the experiments. The wood used is from the debarked stems which are processed in the mill. The round sides of the stems are chipped in a first step, sieved and piled up. The chip fraction was chosen for the experiments. The wood chips are around 4-5 cm in length and about 1 cm thick. This material is milled with an industrial cutting mill (Wanner c17.26sv) with a 6 mm sieve (round holes). The particle size distribution is given in
Figure 3.3. This procedure is used to be able to use different woody biomass fuels from different sources and to keep the particle size and shape within an acceptable range.

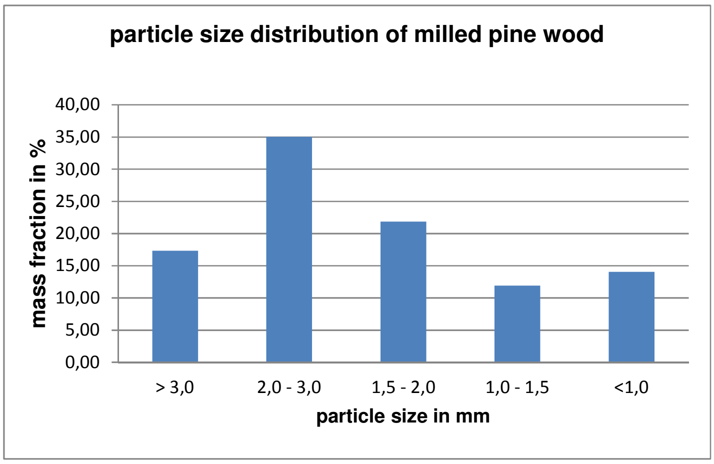


Figure 3.3: Particle size distribution of the milled pine wood used for the experiments.

The wood has a very low content of ash. When received the moisture is around 50 %. It is dried before using it in the gasifier. The properties of the wood are given in Table 3.1.

Table 3.1: properties of the pine wood used in the experiments

proximate analysis			
	volatiles	wt.%	82,29
	Ash	wt.%	0,18
	Water	wt.%	8 - 12
ultimate analysis			
	C	wt.%	49,10
	H	wt.%	6,71
	N	wt.%	0,06
	S	wt.%	0,10
	O	wt.%	43,87
Higher Heating Value			
	HHV (dry)	MJ/kg	20,12

3.2.3 Bed Material

The fluidized bed at TUB is operated with a charcoal bed. Research is carried out about the conditions under which tar develops and it is further examined how tar and char react under varying reaction conditions. The pressure drop is much less compared with sand-like materials such as quartz sand, olivine, dolomite or aluminium oxide. However, the operation is limited to a smaller range equivalent ratios depending on the fuel properties and temperature settings of the reactor heating. If leaving the range bed material is either consumed or will build up within the reactor. The capabilities of tar removal by char are known and under research. So far mainly beds of char in the downstream or in batch experiments are examined. In the work at TUB char as active bed material is used. The properties of bed material as well as that of the hot gas filter residues recovered after an experiment are given in Table 3.2.

Table 3.2: Properties of the bed material from the fluidized bed and of the Hot Gas Filter (HGF) residue resulting from the experiments with pine wood

			Bed material	HGF residue
proximate analysis				
	volatiles	wt. %	2,75	13,08
	ash	wt. %	6,70	21,18
	water	wt. %	0,18	0,00
ultimate analysis				
	C	wt. %	88,53	71,93
	H	wt. %	0,73	1,64
	N	wt. %	0,25	0,55
	S	wt. %	0,01	0,06
residual	O	wt. %	3,78	4,64

It is obvious and expected that the charry material has a high carbon content. It can also be clearly seen that ash material is blown out of the reactor by the much higher ash content of the filter residues. Particles smaller than ~ 0,2 mm will be carried over. This can be seen in Figure 3.4 where the particle size distribution of the charcoal bed is represented.

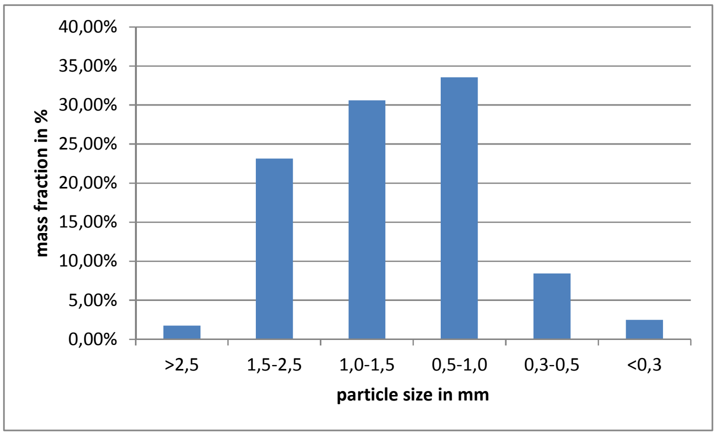


Figure 3.4: Particle size distribution of the charcoal bed material after the gasification experiment

Comparing with the particle size distribution of the wooden feedstock it can be seen that the medium particle size shifts from about 2 - 3 mm to 1,0 - 2,5 mm. There is some shrinkage but also attrition and reaction of the carbon materials.
The bed material shows different bulk densities between 70 and 90 g/l and BET surface areas in between 100 and 300 m²/g. This depends on the ER and local reaction conditions which could be further influenced by adding steam or by other solid reactive bed materials.

3.2.4 Operation of the gasifier

Gasification was carried out at ER's around 0,22 - 0,30 and reactor temperatures around 800°C. The freeboard temperatures rose slowly to nearly 800°C in the first segment and were about 680 – 700°C in segment two. In a larger system without heating but proper insulation of the reactor vessel temperatures in the bed are expected to be lower due to the given ER. In Figure 3.5 the temperature distribution along the reactor is shown. The lowest temperature is that of the preheated air.

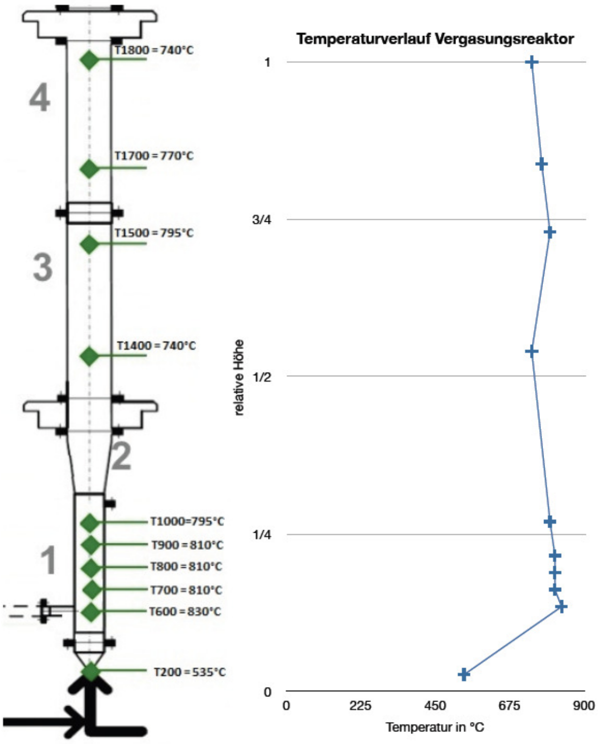


Figure 3.5: temperature distribution in the reactor

In the following Figure 3.6 the temperature distribution during a consecutive run is shown. As can be seen the bed temperature really fast reaches desired reaction temperatures around 800 ℃. The temperatures in the freeboards need about 2 hours to reach values as expected. This is due to slow heating but also to the endothermic reactions taking place. For the measurements to be taken this slow temperature increase is not of benefit because other system parameters like tar content change with it.

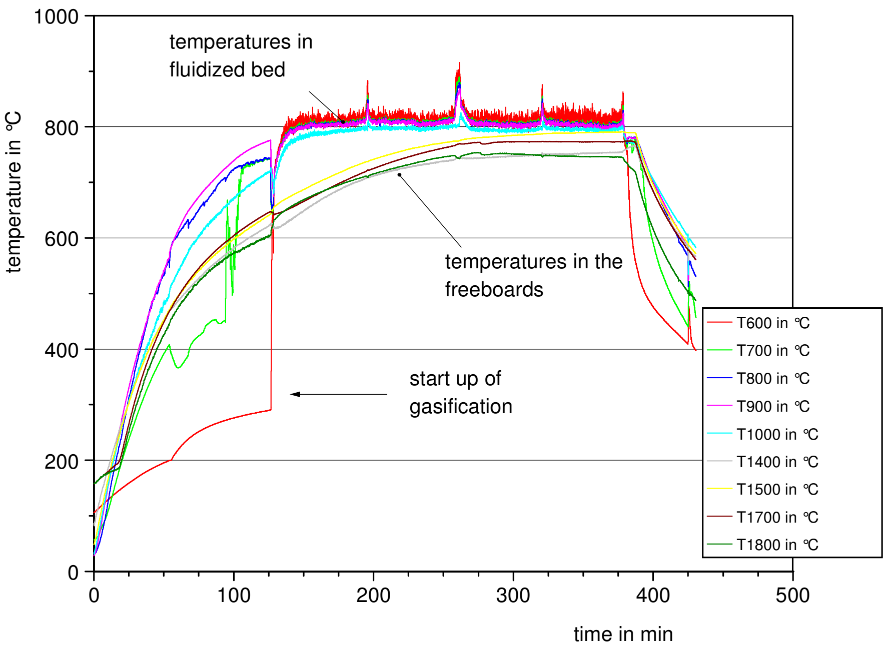


Figure 3.6: Temperatures in reactor and freeboards during typical gasifier operation, for the position of thermocouples refer to Figure 3.5

The reactor is operated with a feed of about 3 kg/h milled wood chips and an air flow of 52 nl/min. This results in an ER of 0,25. The pressure drop across the bed of char is very low compared with other publication where beds consisting of sand, dolomite olivine or alumina are used. Figure 3.7 shows the pressure drop during the run.

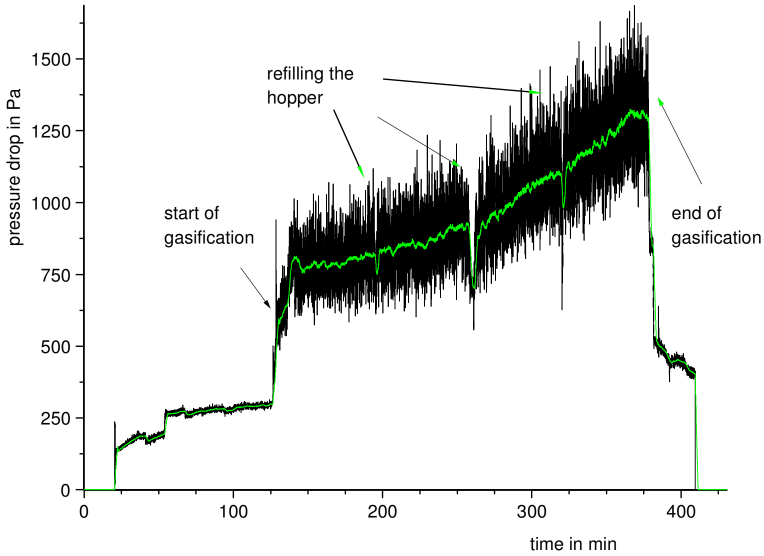


Figure 3.7: Pressure drop across fluidized bed of char, green line smoothed values

In the following table the gas composition is given. During the different runs interesting observations were made regarding the content of butane. It changed from nearly nothing to close to two percent during runs. If so the heating value of the gas is highly effected because butane has with 122,9 MJ/Nm³ a high heating value. Compared with Methane (35,9 MJ/Nm³) or the average gas heating value of the product gas of 5 - 7 MJ/Nm³ this influence is obvious. The effect of butane occurrence is under further investigation. But it was also seen that organic media dissolve butane readily. In the gas analysing cabinet for oxygen control of the ESP no butane was measurable. It was most likely washed out by the Diesel used to remove tar from measurement gas.

Table 3.3: gas composition from fluidized bed gasifier

gas component		Vol. - %
nitrogen	N_2	45,84
carbon dioxide	CO_2	14,05
hydrogen	H_2	14,34
carbon monoxide	CO	19,55
methane	CH_4	4,38
ethene	C_2H_4	1,43
ethane	C_2H_6	0,17
propene	C_3H_6	0,00
propane	C_3H_8	0,00
butane	C_4H_{10}	0,24

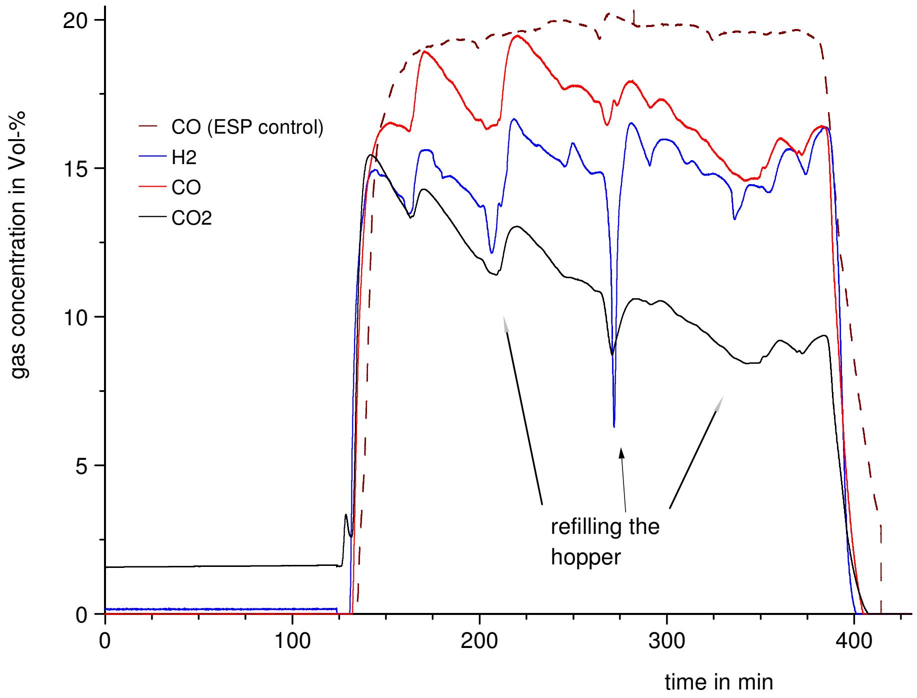


Figure 3.8: Gas compositions measured during gasification run.

In Figure 3.8 monitored gas compositions are shown. The sampling and analysis with the continuous gas analyzers (TCD for H_2, NDIR for CO and CO_2) showed difficulties during the runs. More detailed analysis were therefore made on the basis of using separate gas sampling and analysis by off-line GC/TCD. Results were shown in Table 3.3.

3.2.5 Operation conditions of the Hot Gas Filter (HGF)

A hot gas filter (HGF) with three (3) ceramic filter candles (Dia-Schumalith 10-20 by Pall Schumacher; 0,3 µm pore diameter) is used to separate particles of ash and char from the product gas to get a nearly dust free gas. The HGF was designed for a gas flow rate of up to 10 Nm³/h, dry with a maximum pressure drop of 5.000 Pa at operation condition. Maximum design temperature of the HGF is 500℃. The vessel of HGF is electrically heated by two (2) heating bands, each with a power of 2.5 kW and a maximal operating temperature of 450℃. Thermal insulation of vessel with two (2) layers of glass wool insulation material on the one hand minimize heat loss and on the other hand ensures an outer surface temperature of insulated HGF vessel below 150 ℃ as contact protection. The hot gas filter can be cleaned by back pulsing with (nitrogen pressure between 1.5 and 2 bars) to prevent permanent blocking of ceramic filter candles with tar and particles.

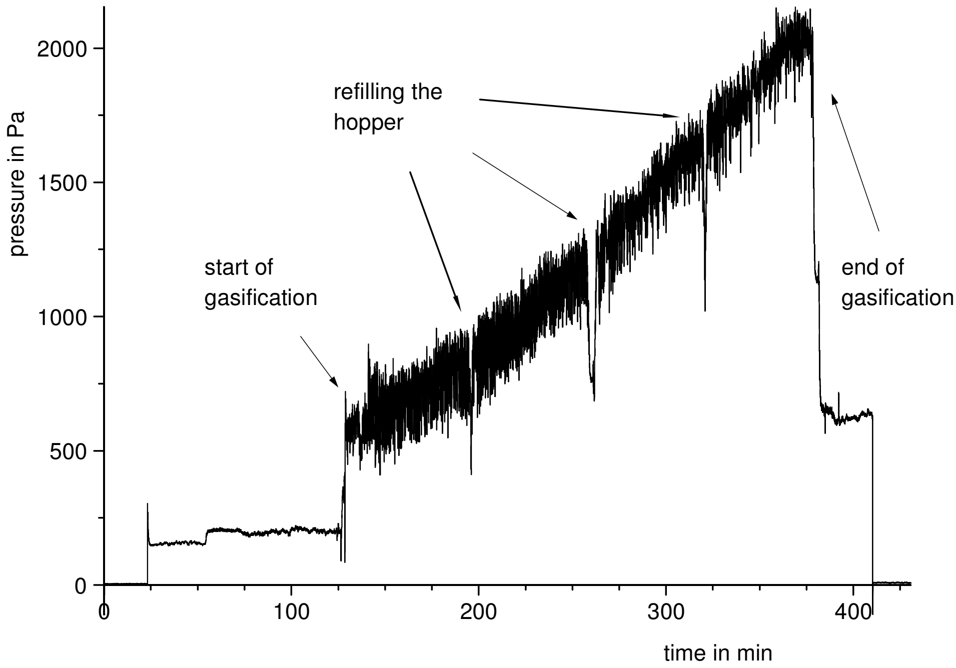


Figure 3.9: pressure drop build up in the hot gas filter in a consecutive run for about 4 hours

In Figure 3.9 the behavior of the hot gas filter in the gasification system is depicted. Shown is the build-up of pressure drop by the filter. This pressure builds up in all upstream parts of the plant, seen from the position of the filter, which are reactor and fuel feed.

3.2.6 Operation conditions of quench and electrostatic precipitator

The operation conditions of quenching system and ESP are discussed in more detail in chapter 5.

3.3 Analytical work

TUB performed different analytical tasks within the project. In the analytical laboratory fuel and residues of the process were analyzed. For that proximate and ultimate analysis of different fuels such as pine wood (results presented) and short rotation coppice poplar and willow wood were realized. In the project it was later decided to stay with one representive biomass to produce comparable and repeatable results. This was special importance to compare the four heat exchangers from ERK. But also for the measurements with quench and ESP and later with the Mop-Fan added to the system it was the better choice to have same or nearly same operating conditions throughout the project. Some tests with willow were carried out after finishing the project.

Gas analyses at the gasification plant were done with online-measurements as well as with off-line analysis.

Online monitoring of the gas components was performed with NDIR (Leybold-Heraeus, Binos 1.2) for CO and CO_2. Hydrogen was monitored with a thermal conductivity detector (LFE, Conthos).

For offline gas analysis with GC/TCD samples were drawn into glass sample containers and were analyzed later on. The GC/TCD applied (HP 5890) is equipped with a Porapak and a molesieve column. Nitrogen and helium are used as carrier gases. With this system the analysis of CO, CO_2, H_2, hydrocarbons C1-C4, N_2 and O_2 was performed.

Tar was analyzed by different means. In the beginning of gasifier operation in the project tar protocol was applied. The GC/MS faced technical problems at that time which were finally solved by changing the turbomolecular pump. Because of that gravimetric analysis of the sampled tar was used to get results. The values ranged in between 4 and 6 g/Nm³. Some tests with SPA were done to compare the data.
Also the prototype of the new developed online Tar analysis system CONTAR [Neu/2010a] was used in some of the gasification runs. The major tar analysis work was carried out using online coupled GC/MS [Neu/2008]. Here a GC/MS (Varian, Saturn 2100) is connected to the plant via heated pipes. The gas is drawn over a 6-port-valve to let 250 µl of sample at about 300℃ into the system. The tar species are separated on a 30 m capillary column (Varian, VF-5ms). Results of the GC/MS measurements are shown in the respective chapters of this report.

With the project a Fourier Transform Infrared-Spectrometer (FTIR) was acquired. Goal was online monitoring of some contaminants like NH_3 in the gas before and after Quench/EPS and Mop-Fan. Furthermore the examination of the behavior of light hydrocarbons C1-C5 plus benzene was intended. FTIR is capable of measuring in a broad concentration range from ppm to percent and can quantitatively analyze a large number of species.
The system was first placed after the gas monitoring (O_2-control) of the ESP in order to obtain a tar free gas to be analyzed. On one hand the ESP went quite late in the project into operation so that the available time for measurements was less than initially planned. On the other hand the gas treating system of the O_2-control unit that was intended for hooking up the FTIR took out tar well but also left diesel from the initial tar washing stage in the gas so that the requirements of the FTIR were not met. So measurements were performed drawing samples directly behind the quench/ESP system where less problematic tar species are present in the gas.

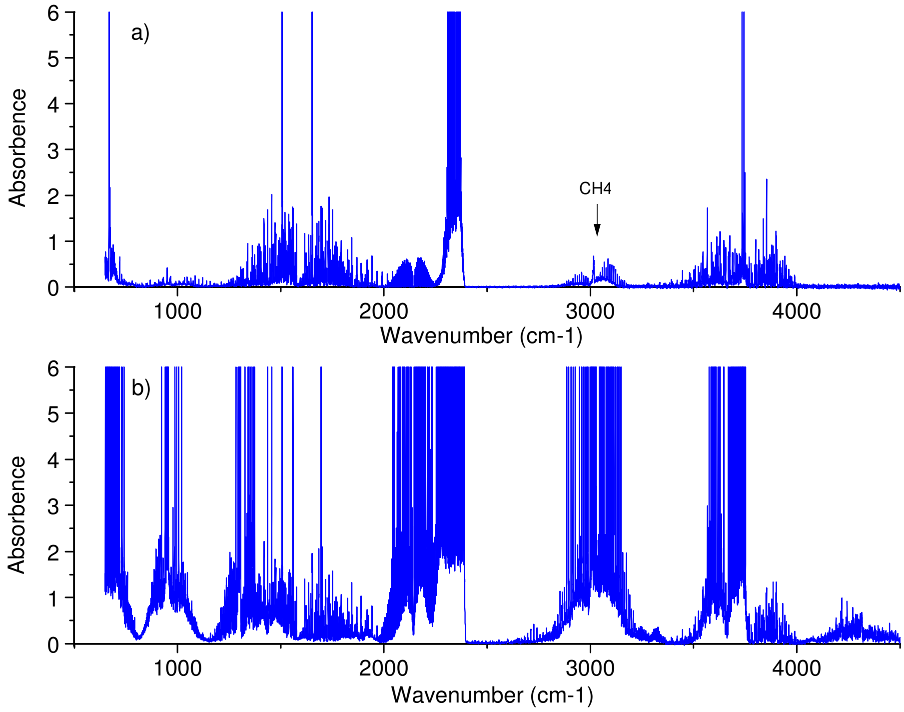


Figure 3.10: Gas analysis performed with FTIR in EMF project; a) gas drawn from cold plant in between test with nitrogen purge present b) online measurement during gasifier operation

Solving all the sampling related problems in addition to some errors from the device (pressure metering for result correction) occurred so that here no validated results can be presented. Some first results shall be presented anyways.

In Figure 3.10 absorbance spectra recorded with the FTIR are shown. Spectrum a) is acquired from the cold plant one day after shutdown. The gasification system was purged with nitrogen as described before. Still gas components from the product gas can be measured by the FTIR. The second spectrum b) is from hot operation of the plant. The sampling point was between ESP and Mop-Fan. Some gas compounds like CO, CO_2, H_2O are at high concentration near the concentration limits (over saturation) of the device. Anyhow they can be determined and analyzed as well but the right wavenumbers for analysis have to be selected. This is a still ongoing process. As mentioned with the butane content in the gas this will be one of the applications the device will be further used for.

4 ERK Eckrohrkessel GmbH - structured tube heat exchanger

ERK Eckrohrkessel GmbH participated in the project “Mop fan and electrofilter: an innovative approach for cleaning product gases from biomass gasification (EMF)” as a subcontractor of the TU Berlin, Institute of energy engineering, Chair EVUR. The main research task in this field has been the application of high-performance heat exchangers of the vertical type based on structured surface technology. Industrial power tube® is a trademark of structured tubes with functionally designed surfaces owned by ERK Eckrohrkessel GmbH (Fig. 4.1). The gas cooler in particular had been fitted directly over the freeboard on the top of the gasifier and exposed to the hot raw gas. This arrangement was essential to recover as much of the sensible heat of the producer gas as possible, because the integration of this thermal energy into the gasification process again, for example by drying the fuel or preheating the air supplied to the gasifier, contributes significantly to an increase in the overall efficiency of the whole process chain.

Figure 4.1: Selected industrial power tube® for the enhancement of heat and mass transfer.

4.1 Construction, design and dimensioning

Firstly, for purposes of construction, design and dimensioning affairs specific engineering criteria were established, which could be used for the assessment of the possible features of the product gas coolers. Primarily the operation mode of the fluidised bed gasifier and its characteristic data had to be taken into account, such as gas velocity, temperature and viscosity, particle load and size distribution as well as that of tars. In addition, the dew point of the major tar constituents and moreover the material resistance against heat stress and corrosion besides the fabrication efforts and costs had to be considered. In principle ambient

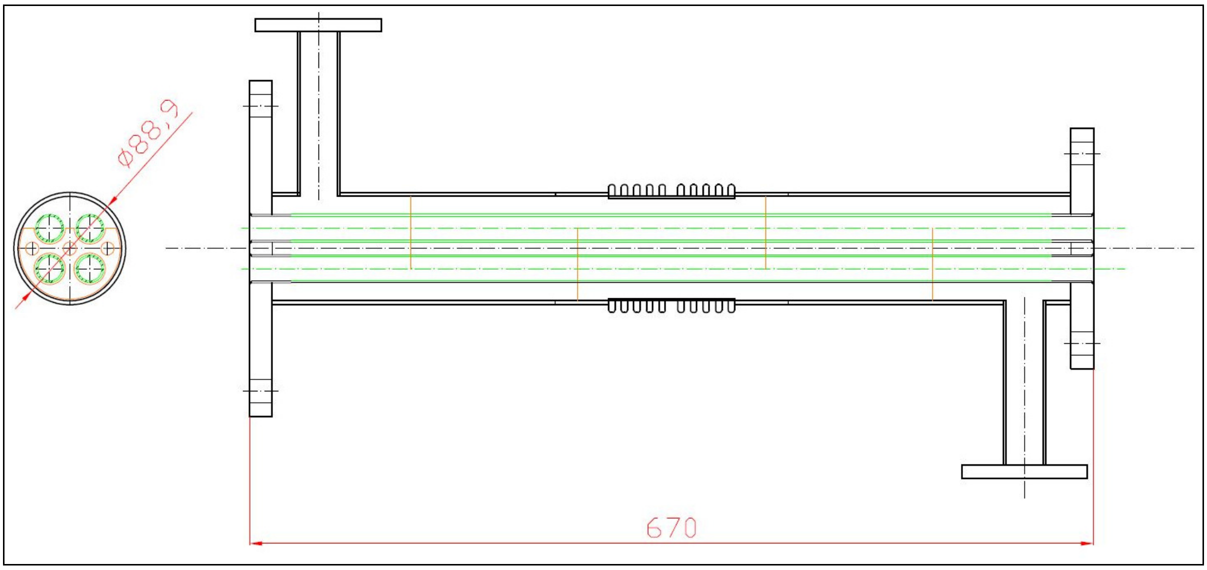


Figure 4.2: Layout of a gas cooler with a cubic bundle of structured tubes in dense package.

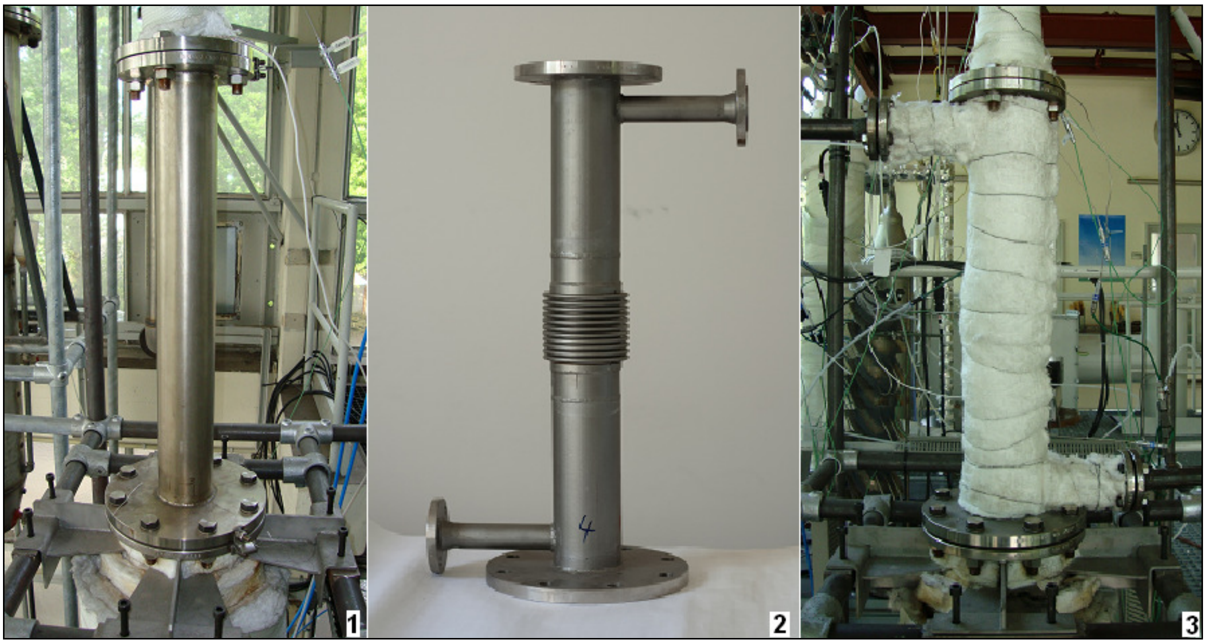


Figure 4.3: Blank module (1), ip tube® heat exchanger (2), heat insulation (3).

air, thermo-oil or process water could serve as a coolant. In particular a design of an air cooled heat exchanger has been preferred, because the best heat transmittance could be expected using ip tube®. Relevant accelerations of the gas, which would lead to local wall contact, could only be avoided by applying a design of the vertical type (Fig. 4.3.2). Based on a matrix method to assess the above mentioned features under the given operation conditions a layout for a high-performance gas cooler has been implemented that did come to scratch (Fig. 4.2):

- concurent gas-air-cooler,
- bundle of four corrosion resistant stainless steel structured tubes in cubic dense package,
- four diversion plates on the air side and a central compensator in the outer mantle.

In contrast to that for example Huber et al. used a different design [Hub/2008]. To recover as much sensible heat from the gas as possible the heat exchangers had to be placed directly over the freeboard at the top of gasifier (Fig. 4.3.3).
For purposes of detail engineering and particularly regarding the functionality of the ip tube® the admixtures of tar and water vapours as well as suspended particles had to be taken into account. Focussing the state of fluidisation of the gas it could be characterised as a laminar sheer flow. In fluid mechanics a somehow complex or even irregular cross section of a boundary surface can be transformed into an equivalent regular one - the so called hydraulic diameter d_{Hyd}. In the case of structured tubes d_{Hyd} is proportional to an expression of the inner volume V_i and the wetted surface Ai (Tab. 4.1). V_i had been determined volumetrically, while A_i had to be calculated on the basis of a so-called Fourier-Model (Chap. 4.4). From the rheological point of view the product gas must be characterised as a dilute suspension of particles, water and tar vapours in a mixture of gas components. Following a statistical model of spheres superseding the basic fluid the effective viscosity η_{eff} of such a relatively simple Non-Newtonian Fluid could be calculated approximately by using an expression of the undisturbed gas mixture and the volume fractions of the suspended constituents. Although the resulting effect is not a very drastic one, nevertheless it could not be neglected to achieve accuracy in analysis and calculation. Therefore the Reynolds number has been quantified to be of the order of Re = 500 - 1500.
Based on a semi-empirical theory for the enhancement of heat transfer one of the most important parameters is the corresponding recirculation length l_R of the gas flow downstream a dimple. In the given case the value of l_R had been between 15 - 45 mm. Consequently the space between dimples s_S equidistantly have been designed in that range.

Table 4.1: Characteristic parameters of ip tube® used for the design of the heat exchangers.

Characteristic parameters of ip tube®					
Parameter	Symbol	Value #			
		1	2	3	4
Outer diameter	d_a	21.3	21.3	21.3	21.3
Inner diameter	d_i	18.3	18.3	18.3	18.3
Depth of dimple	t_S	-	2.0	2.5	3.3
Dimple distance	s_S	-	18.0	30.0	42.0
Hydraulic diameter	d_{hyd}	18.3	17.6	17.5	17.2
Free diameter	d_{min}	18.3	14.3	13.3	11.8
Inner Volume	V_i	176.2	172.5	173.0	173.5
Wetted Surface	A_i	356.5	360.0	363.5	370.7
Offset angle	α	-	60		
# Model No., mm, cm^3, cm^2, °					

Following the working hypothesis that the inner volume Vi of the structured tubes should kept constant, their depth tS has been estimated to be 2 to 3.5 mm (Tab. 4.1). The shape of the dimples is conical, three of them are evenly distributed over the annulus, the offset angle between annuli is 60°. Therefore the surface structure causes the following effects:

- Periodical acceleration plus dilatation of the gas flow,
- Increase of the active surface of the tube exposed to the incident flow,
- Increase of the general grade of turbulence by nearly completely disturbing the viscous boundary layer, generating a turbulent sub-layer and affecting relevant amounts of the inner core flow,
- Induction of vortices of a significant strength thereby leading to increased dispersion with a reduction of fouling as well as a re-fluidisation of deposits.

A more comprehensive description had been given elsewhere [Hel/2005; Neu/2010].

4.2 Experimental Results

All of the experiments were carried out at the test facility of the EVUR (TU Berlin). At first the whole experimental set-up including each of the components of the gasification process and the measurement equipment had to be installed. In a second step preliminary tests of the elements of the construction were carried out using blank modules or dummies (Fig. 4.3.1). Having finished these investigations each of the gas coolers has been integrated into the gasification unit and the hot gas line to execute the test runs (Fig. 4.3). The experimental set-up for the test series allowed to record all relevant in- and outflows as well as the operation conditions of the system and at its boundaries (Fig. 4.4 left). After this test runs had finished, an additional campaign of control measurements was carried out using a more refined special experimental set-up with the aim of establishing heat and mass balances as accurate as possible (Fig. 6.4 right).

During the test runs as well as the control measurements the product gas flow was kept constant at 6 $m^3 \cdot h^{-1}$, referring to the normalized state. The product gas composition and the particle load, their size distribution as well as the tar freight were more or less as expected (Chap. 3).

Firstly, orientating measurements had been carried out to estimate the operation point of the heat exchangers practically by varying the volume flow of cooling air systematically between 20 - 60 $l \cdot h^{-1}$ (1.2 - 3.6 $m^3 \cdot h^{-1}$) on a trial basis (Fig. 4.5). The following test runs have been

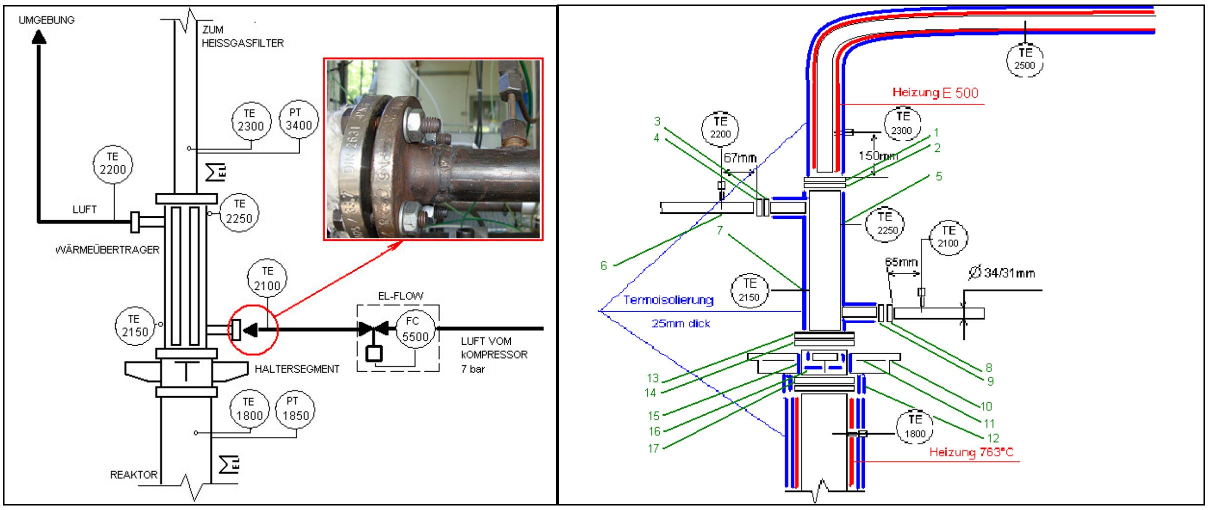


Figure 4.4: Experimental set-up for test series (left) and for control measurements (right).

performed at a constant volume flow of 35 $l \cdot h^{-1}$ (2.1 $m^3 \cdot h^{-1}$, Fig. 4.6) or 40 $l \cdot h^{-1}$ (2.4 $m^3 \cdot h^{-1}$, Fig. 4.8) during control measurements. For purposes of balancing, too, another type of orientating measurements was carried out to investigate the impacts of varying product gas temperature as well as the influences of changes in the heat insulation on the side of the coolant (Fig. 4.6).

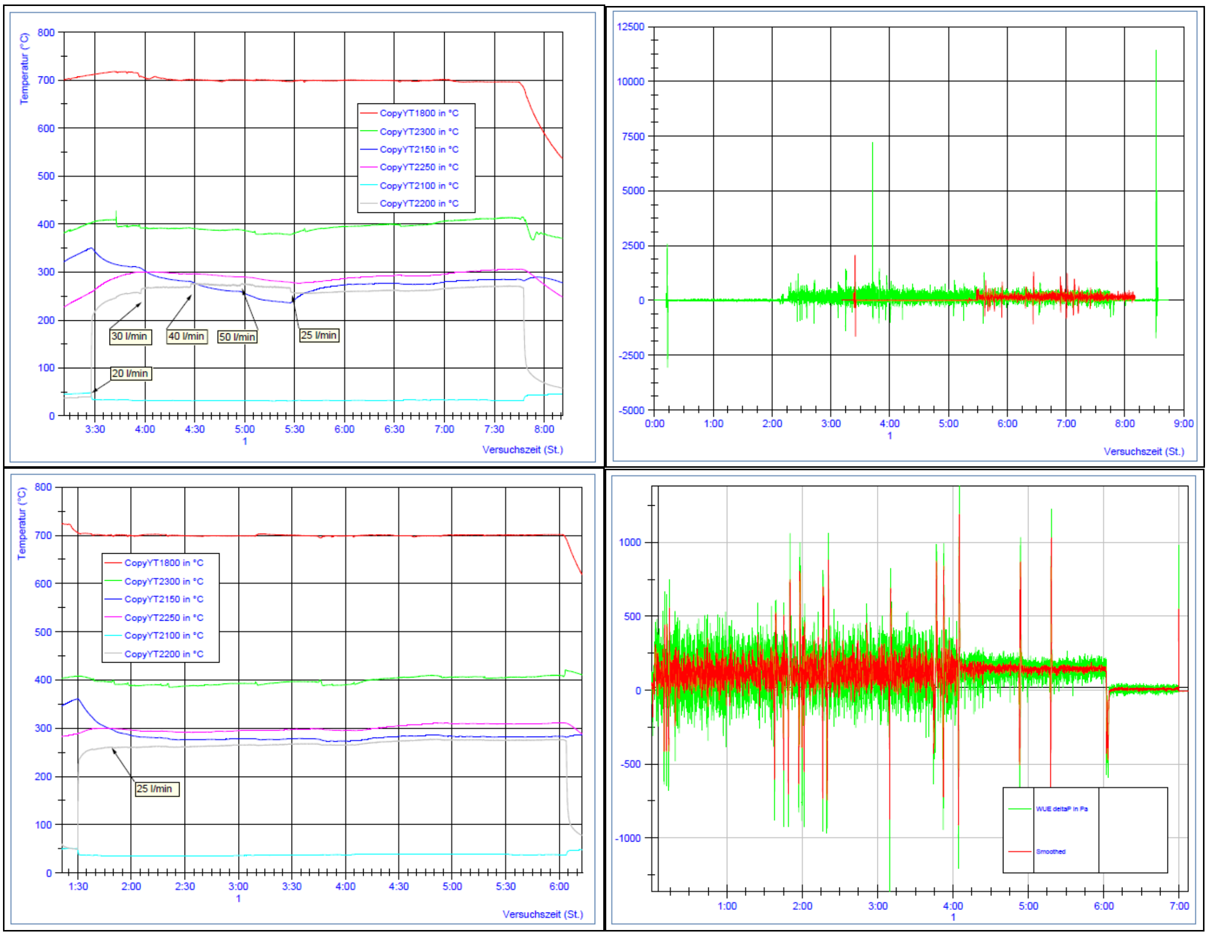
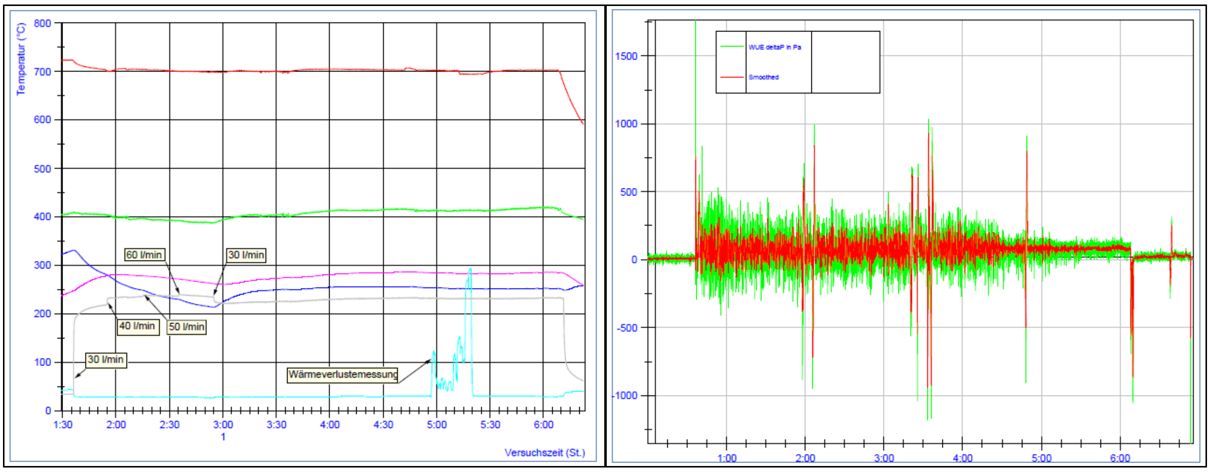


Figure 4.5: Heat Exchanger Model No. 4 - Process temperatures and corresponding pressure loss during the orientating measurements (top) and the test runs (bottom).



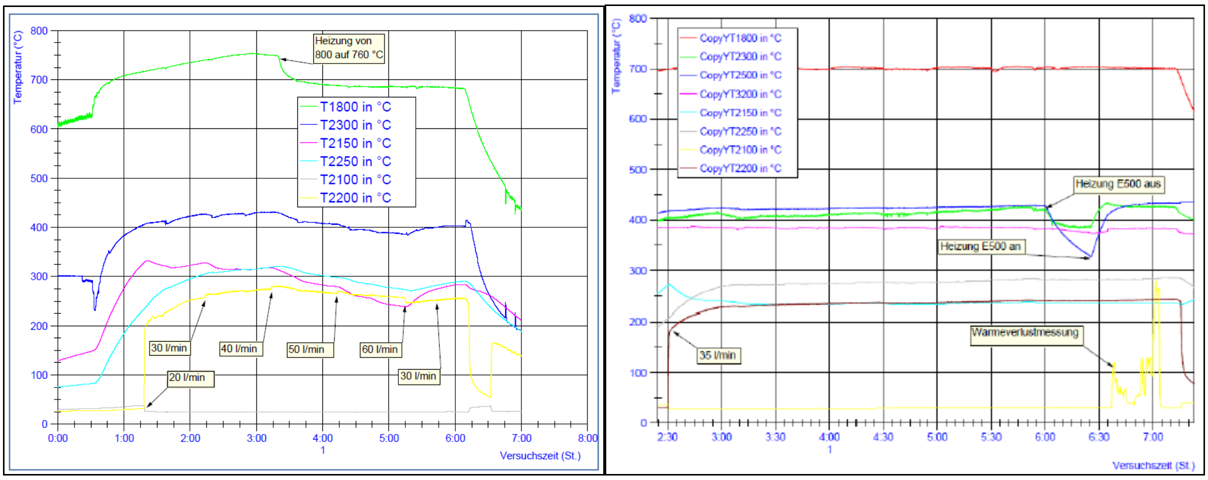


Figure 4.6: Results of orientating measurements - Mod. No. 2 (top, bottom right) and No. 3.

The most important results of the test runs can be summarised as follows: All of the gas coolers worked excellently well. Each Model 1 - 4 has been capable to cool down the product gas from nominally 700 °C to 400 °C (Chap. 4.3). The corresponding pressure loss had values of some dozens Pascal (Pa) and is a few Pa higher than in the cases both of smooth tubes or pure gas, as expected (Tab. 4.4). Because of the pressure fluctuations induced by the fluidized bed as well as the particle load on the gas side at the first sight the pressure difference over the heat exchangers appears much greater than it really is (Fig. 4.5, 4.6). In any case the cooling air was definitely heated up from approximately 40 °C to 300 °C. Even during test runs longing for 16 hours no complications occurred that would have afflicted the defined mode of operation. According to the state of the art the quantitative determination of accumulated deposits or the probing of fouling processes would require test runs longing for some 100 hours and each gas cooler. In the project reported here only a fraction of this duration could be reached as it was foreseeable. Therefore the accumulation of deposits qualitatively has been found to happen in that way, that initially some species of tars are condensed on the walls, which in turn become the glue to which the more granular, brittle ash stick (Chap. 4.3).

4.3 Balances

The experimental data given in this whole chapter only on the forehand appear as if it were smooth time dependent functions of each parameter. But one has to keep in mind that in reality it represents only a series of discrete snapshots of a large amount of strictly arranged single values related to each other. Nevertheless, in principle it should be possible to derive

Figure 4.7: Improved experimental set-up during control measurements for balancing.

a close description of the systems behavior from that, which would represent a differential balance. For several reasons systems like gasifiers having reached thermal equilibrium and even more if operated with solid fuels do not become stationary at all [Klo/1997; Fer/2002]. Besides starting up and shut down processes there are transient states caused by changes of power load, fluctuations of the fuel size and composition, the gasification agent, temperature and pressure profiles in the reactor and so on.
To meet these circumstances the original experimental data were reduced to periods within the test runs, e. g. to one hour, in which the measured parameters could be esteemed to be free from fluctuations or nearly constant. In these circumstances the term reduction indicates, that only selected experimental data were used to establish integral energy and mass balances with some accuracy. With respect to gasification this method had already been proposed before [Wit/1993]. In the project reported here the experimental data were selected and assessed statistically to get the arithmetic average, error interval and standard deviation using the Software-Tool DIADEM (Tab. 4.2). Moreover, to increase the accuracy of balancing an improved experimental set-up has been used to gain additional data which would be necessary to contribute to a better knowledge of the process (Fig. 4.7). In particular, the local conditions on the primary product gas side were of greatest importance to close the energy

Table 4.2: Statistical analysis of experimental data over a period of 2.5 h (900 snapshots).

Statistical analysis of experimental data						
Parameter	Symbol	Unit	Equipment No.	Arithmetic average	Standard deviation	Statistical error
Gastemperature, Inlet	$T_{G,i}$	°C	1800	700.9	2.0	0.01
Airtemperature, Inlet	$T_{A,i}$		2100	28.3	0.9	0.01
Walltemperature, Inlet	$T_{W,i}$		2150	234.4	1.4	0.01
Airtemperature, Outlet	$T_{A.o}$		2200	235.0	3.4	0.02
Walltemperature, Outlet	$T_{W,o}$		2250	275.5	3.8	0.03
Gastemperature, Outlet	$T_{G,o}$		2300	413.2	5.8	0.04
Heat Exchanger model No. 2, selected data set No. 5 (Fig. 4.6 bottom right)						

Table 4.3: Energy balance of a selected heat exchanger (4) and the reference model (1).

Items of the heat balance						
Quantity	Symbol	Unit	Heat Exchanger Model No.			
			1		4	
			absolute	fraction	absolute	fraction
Input						
Sensible heat of the gas	$P_{SH,G}$	W	360	1	427	1
Output						
Radiation mantle	$P_{Rad,M,A}$	W	- 87	0.24	- 87	0.20
Thermal conduction flans	$P_{Tc,F,A}$	W	- 47	0.13	- 47	0.11
Dispersion tubeplate in	$P_{D,Tp,i,G}$	W	- 30	0.08	- 30	0.07
Dispersion tubeplate out	$P_{D,Tp,o,G}$	W	- 9	0.03	- 9	0.02
Recovered heat	$P_{RH,A}$	W	- 187	0.52	- 254	0.60
Heat transmittance	k_i	$W \cdot m^{-2} \cdot K^{-1}$	8.7		11.1	

balance. Therefore some efforts had been made to the application of additional thermocouples to the product gas flow for the measurement of the temperatures at the in- und outlet of the heat exchangers in situ or directly. By doing so, the quality of the heat balance could be augmented significantly, while the uncertainties related to the heat losses by radiation, thermal conduction and dispersion were nearly be eliminated (Tab. 4.3).
According to the energy balance the overall heat transmittance k_i of the model No. 4 equipped with structured tubes for example was determined to be increased by about 30 % in comparison with the conventional model No. 1. About 500 Watt of the sensible heat of the product gas could be used by the cooling process, a value depending strongly on the operation conditions, of which 60 % could be recovered and transmitted to the cooling air. Therefore the power output of the heat exchanger models with structured tubes was 15 % higher than the conventional one at all. In any case the unavoidable heat losses by radiation, thermal conduction and dispersion amounted to 40 - 48 %, which at the first sight seems to be quite large. But one has to keep in mind that due to small absolute dimensioning of the heat exchangers scale effects play the significant role limiting the overall thermal efficiency to at least $\eta_i \leq 0.6$. In other words if the devices´ dimensioning would be a factor of 10 greater than it is in the case given here the heat losses could be reduced to about 10 % of the thermal

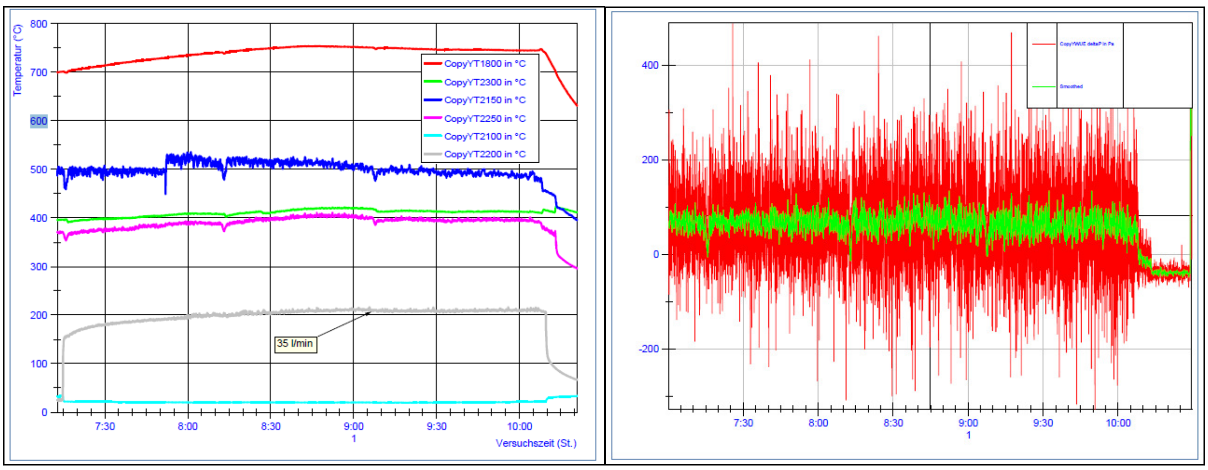


Figure 4.8: Results of control measurements - Model No. 4 (Tab. 4.3).

Table 4.4: Pressure loss of the heat exchangers.

Pressure loss						
Quantity	Symbol	Unit	Heat Exchanger Model No.			
			1	2	3	4
Average value	Δp	Pa	70	78	76	89
Confidence interval (68.3 %)	-	Pa	-	2.9	-	18.6

power or even less. The heat transmittance k_i is proportional to the inner heat transmission αi from the gas to the tube wall, the outer heat transmission αo from the wall to the cooling air and an expression of material constants, namely the specific heat conductivity λ and the wall thickness s. While α_i can somehow be easily estimated by experiments with single tube probes, it is rather difficult to measure the outer heat transmission αo on the air side because it´s a function of the design of the gas cooler, too.
The corresponding total pressure loss Δp on the gas side is an important characteristic value indicating the energetic and economical expenditures needed [Chu/2006]. The measurement has been rather difficult because of the small values and the disturbances by the fluidised bed (Fig. 4.8). In any case Δp did not exceed 100 Pa and was increasing with decreasing hydraulic diameter (Tab. 4.4). Additionally a weak evidence of gently increasing pressure loss with cumulating time of service life has been observed.
With respect to the effectiveness ε_i of a certain measure of heat transfer enhancement there exist a handful of different formulations of characteristic values [Ste/1984]. In a first approach according to similarity theory it is suitable to express ε_i by a dimensionless compound fraction of the augmented k_i in relation to k_0 of the conventional heat exchanger model divided by the resulting Δp_i in relation to the original Δp_0, respectively. Taking into account the magnitude of the confidence interval for example the increase in effectiveness of the heat exchanger model No. 4 figured out to have a positive value of about 5 %, which indicates an important overall benefit resulting from the particular method to enhance the heat transfer.
With respect to fouling it has been found qualitatively that the accumulation of deposits happened in that way, that initially some species of hydrocarbons condensed on the inner tube walls, which in turn become the glue to which the more granular, brittle ash stick (Fig. 4.5). With increasing exposition time a wall near part of the initial layer were carbonised forming a coke sub-layer. Approximate analysis of the layer with chromatographic-mass spectrometric methods demonstrated, that the major constituents were condensates of 2- to 4-ring aromatic hydrocarbons [Neu/2010a]. On this basis an estimation of the deposited mass has been carried out, which showed, that under the defined operation conditions roughly not more than one hundredth of the initial hydrocarbon freight or 30 mg $\cdot$ m_N^{-3} should have been separated on the tube walls during the experiments. Taking into account the specific boiling points of the identified hydrocarbons it has been supposed that some of the compounds must have been deposited due to transient states of operation, e. g. start up and shut down processes (Tab. 4.5). Generally this could have only been avoided by using a bypass installation, although a blank module has been installed during preliminary tests (Fig. 4.3). Additionally somehow an improved quantitative measurement of accumulated deposits or the probing of the fouling process would have required much more test runs for each gas cooler. Even the elegant gravitational determination of deposits has not been possible in the duration of the concise project because of the formidable expenditures in material and time.

4.4 Numerical Calculations

It is often very instructive to carry out numerical calculations of fluid flow, because the different phenomena can be analysed much more in detail. The results focusing a representative ip tube® of the heat exchanger model No. 3 generated with the software tool Computational

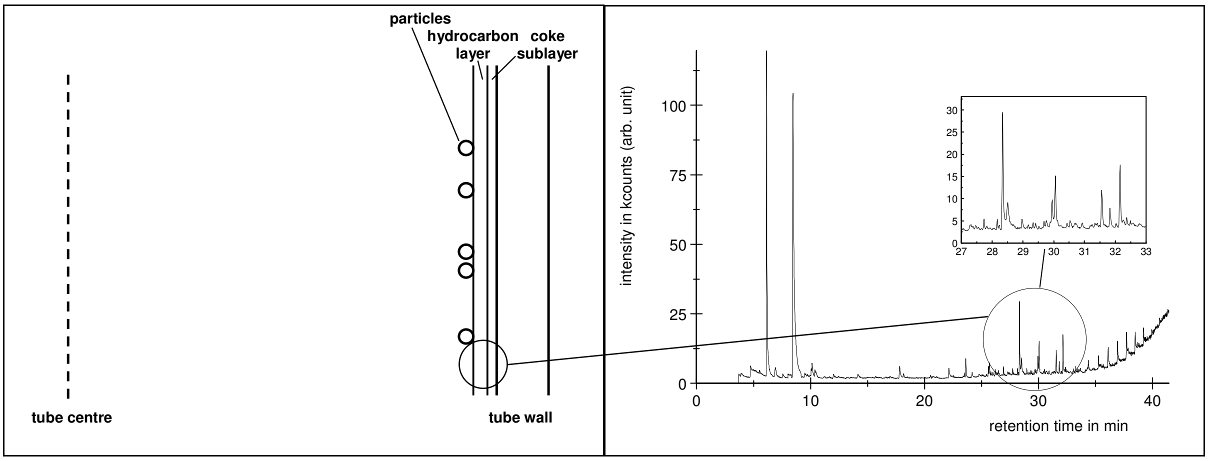


Figure 4.9: Deposit analysis regarding assembly (left) and hydrocarbon components.

Table 4.5: Characteristic data of the detected hydrocarbon components [Hay/2010].

Hydrocarbon layer components						
Substance	Acenaphtylen	Biphenylen	Fluoranthen	Fluoren	Phenanthen	Pyren
Boiling point	240 °C	290 °C	384 °C	295 °C	340 °C	404 °C
Ringnumber	3	2	4	3	3	4

Fluid Dynamics (CFD) are shown below, exemplarily (Fig. 4.10, Tab. 4.1). With regard to CFD simulation of structured tubes we distinguish in principle between so called

- Forming process based models (FPM) and
- Fourier-Models (FM).

The former ones are real physical models, which are consuming very much time, man power and computing power. The latter ones are simplified models based on synthetic methods of synthesising analytical functions for the generation of cross sections and intrinsic curves of ip tube® by superposition techniques - wherefore such models are called of the Fourier type. The somehow complex, but regular and smoothed synthesised field of the tube then is networked and calculated with CFX. For example, the structured tubes of heat exchanger model No. 2-4 have been synthesised out of 40, 70 or 100 conical mantles on the residual cylindrical mantles (Tab. 4.1).
In the same way structures even consisting of different kinds of flat or concave ellipsoidal spheres of had been modelled successfully. Generally the analytical and experimental evaluation of the results of numerical calculations based on Fourier-Models has implied excellent accordance. For example there has been perfect convergence of the numerical calculation in cases of nearly or absolutely zero structure parameters which equal a smooth tube. In analogy with that it should be possible to estimate the local and the overall heat transmittance k_i, if the microscopic energy exchange were considered. In any case the results of numerical calculations one must keep in mind that in many cases these are no direct solutions of the Navier-Stokes-Equations but averaged partial models of the first and second order, which are supported by certain turbulence models.
The results of the numerical calculations in 3 D(imensions) are given here in form of a 2 dimensional plot of the cross section showing a temperature (top) and a velocity profile in the product gas flowing along the tube (left to right) with concurrent streaming cooling air at the periphery on the outer side of the tube wall (Fig. 4.10). In plot 1 the gas temperature at each point of the entrance is 540 °C and there is no radial gradient. Directly behind the first annulus of dimples the forming of the thermal boundary layer is initiated and layer thickness grows until thermal equilibrium is reached near half of the tube length. In the second half the

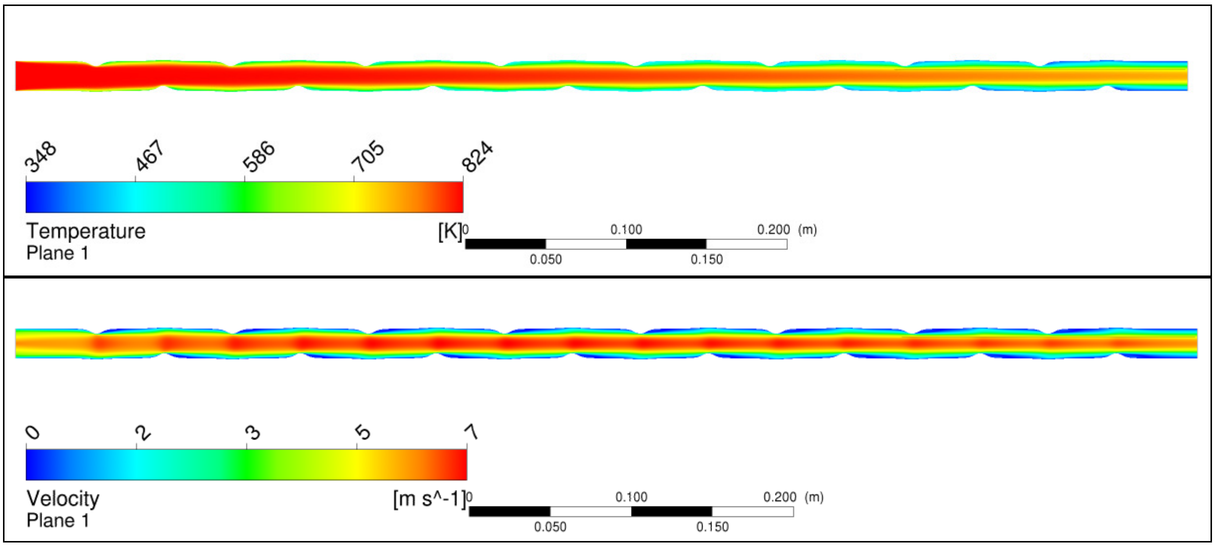


Figure 4.10: Temperature (top) and velocity distribution of an ip tube® model No. 3 (CFD).

influence of the cooling agent dominates, the heat flow is directed outward, the gas cooled down and the mass averaged temperature at the outlet is reduced to 340 °C. With increasing tube length more and more sensible heat is transferred from the gas to the coolant and consequently the gas velocity declines. This can be demonstrated by means of the corresponding plot 2. Namely, the velocity boundary layer is building up directly behind the first annulus of dimples, too. But in opposite to the temperature field the velocity profile then remains undisturbed along the tube, apart from the locally intensified turbulence indicated by the cobalt blue colour induced by the structured surface.

4.5 Conclusions and outlook

During the complete duration of the experimental campaign all of the gas coolers worked excellently well. Each heat exchanger model No. 1-4 was capable to cool down the product gas from the given temperature level directly behind the gasifier to a suitable level to recover as much of the sensible heat of the product gas as possible, while preventing almost all the condensations of hydrocarbons with middle or high molecular weights.

According to the energy balance the overall heat transmittance of the heat exchanger models equipped with structured tubes were found to be increased significantly in comparison with conventional ones. The statistical analysis carried out showed that in any case the strewing of the experimental data was about one order of magnitude smaller than the determined values of the characteristic data. A remarkable amount of the sensible heat of the product gas could be used by recovering and transmitting it to the cooling air while the pressure drop was negligible. Therefore the power output as well as the efficiency of the heat exchanger models with structured tubes was found to be significantly higher than conventional ones at all. The effectiveness of the certain measure of heat transfer enhancement investigated in this project turned out to have a significant positive effect, which indicates an important overall benefit resulting from the particular enhancement of heat transfer by the application of structured tubes.

The numerical calculations carried out by CFD demonstrated, that an intensified local turbulence could be induced successfully, which consequently contributes to the promotion of heat flow from the product gas to the cooling air.

Regarding the physics of scale it came out in that way that because of the relatively small dimensioning of the whole gasification plant with a thermal power of some 15 kW as well as the heat exchangers leads to unfavourable specific losses within the process chain. If, for instance, the thermal capacity of the plant could be scaled up by a factor of three to five, the efficiencies of the components would be significantly higher. Thereby the overall benefit and even more the attractiveness of biomass gasification techniques in general could be maximized.

Particularly in Germany a few ones of the commercially operated gasification plants were equipped with gas coolers, but heat integration was still not practised in any case. On the other hand the recovered heat was mostly used for preheating of the gasification agent and drying of the fuel. Consequently in these cases the overall efficiency achieved was at least a fifth higher than the average [Brä/2009]. A similar but distinct system specific method was put to a good account by reusing the heat from the product gas cooler for the concentration and separation of condensable hydrocarbons extracted from the product gas of an updraft gasification process [Hee/2010]. In this way the heat recovered from gas has been integrated into an allothermal gasification process by preheating the combustion air of the burner in a more model-orientated and evaluating former approach [Klo/2008]. In a comparable, model-orientated work the significant importance of heat integration methods for the energetically and economical optimisation of gasification processes has been shown [Ung/2009]. There is another challenging option of heat integration by generating steam and using it as a gasification agent, e. g. steam reforming of biomass, especially when the reactor is suitable for this process [Bau/2007; deJ/2004; deJ/2006]. A completely different approach of using the hot and cleaned product gas for fuelling a solid oxide fuel cell (SOFC) has been proposed repeatedly [Sch/2010].

Regarding the investigation of fouling processes an approximate mass balance of the heat exchangers could be established. The major constituents of deposit probes, e. g. condensates of poly aromatic hydrocarbons, were detected and an upper limit value of the probable specific fouling rate of hydrocarbons was derived from the analytical data. Moreover the evidence of a segregation of the gas phase suspension has been observed, indicating that the particles with increasing path length accumulate near the tube wall caused by kinetic forces and turbulence. But, mainly because of the restricted duration of the project and the formidable expenditures in material and time required, it turned out to be rather difficult to determine an ultimate mass balance experimentally and to demonstrate the suppression of fouling processes of the heat exchangers equipped with structured tubes clearly.

Due to the definite approach in the EMF-project the appropriable process chain for the conditioning of the product gas at atmospheric pressure has to takes place at 700 °C directly behind the gasifier and 25 °C at the entrance to a combustion engine. Intrasystemic the product gas is subject to several energetic and substantial changes which primarily are induced by the conditioning process. Besides the influences of outer potentials the energy of the gas can be described by an expression of the chemically bound energy, the temperature dependent latent heat of vapors and steam being object to phase transitions and the sensible heat referring to the state temperature, both of the latter two contribute to the heat transmittance of a heat exchanger [Sch/1953].

With respect to fouling the basic description should be quite simple, because the unafflicted heat transmittance k_i is mathematically extended by the heat transmittance k_f due to the deposit resulting in the fouling resistance R_f, a quantity which is depending on exposition time, surface roughness and material [För/1999; Ben/2007]. Usually the exposition time is amounting to hundreds of hours and a non-invasive standard method for the determination of R_f is measuring the specific pressure drop [Alb/2009]. In the project reported here some evidences could be observed, that the determination of an increase in pressure loss of a heat exchanger would take not less than one hundred hours. There is probably an upper limit value of the specific fouling rate of hydrocarbons and the resulting decrease of heat transmittance caused by the deposits should be determined after the project run will be terminated.

It is intended by the participants in the EMF project to publish the obtained results in the near future. In the first instance we would like to contribute to 19th EBCE 2010 in Berlin and the faculty meeting on the energetic utilisation of biomass 2012 in Velen, Germany. Furthermore it is planned to publish more focalised papers in specials journals for example Chemie Ingenieur Technik, Journal of Heat and Mass Transfer and Biomass Conversion and Biorefinery in 2011.

In relation to biomass gasification the application of ip tube® for example has been forwarded while the project reported here was done in partnerships with Agnion Technologies GmbH in the field of heat pipe reformers and the TU Wien regarding methane reforming.

5 Beth Filtration GmbH – Quench and Tar – ESP

5.1 Project goals

As already shown in chapter 1.2 the combination of coolers or washers with ESP's are known for quite some time and are still present in heavy industry. In smaller scale application of biomass gasification this technology has been used in pilot plants or in a commercial setup in Denmark but is not very present on the market. If reviewing literature and consulting experienced pioneers of gasification technology the use of ESP's used to be a standard method for tar removal which has proven functionality over decades. Based on the fact that biomass gasification still faces a major tar problem it is the matter of choice to use and further improve working technologies instead of go on with multiple experiments on the back of unexperienced plant operators in the field. In the EMF project the tar removal capabilities of a system consisting of quench and ESP were object of more detailed examination. It was goal to find out about plant settings and operation conditions to remove tar from a biomass gasifier efficiently. The initial plan was to work with different quenching media (water and RME) and to run the plant with particle free gas (hot gas filter) and with a remaining particle load (cyclone separator). In addition to that different geometries of the electrodes were planned to be tested.
Major goal is to remove tar as much as possible from the gas stream or to reduce the contents of hazardous or harmful tar substances from the gas to ensure safe and reliable operation of downstream equipment.
To reach these goals the partners in the project (Technische Universität Berlin, University of Nottingham and the companies ERK Eckrohrkessel GmbH and Beth Filtrations GmbH) have performed different tests on the lab scale bubbling fluidized bed gasifier installed at TU Berlin. Tar measurements were performed at the inlet of the quench and in the outlet of the ESP to examine the separation efficiency and about the selectivity of tar separation from the gas.
Furthermore the combination of both filter technologies (ESP and mop-fan) and their fields of application were tested for the first time. The experimental data gathered from the collaborative tests is used directly in the dimensioning of new Tar-ESP so that there is a direct connection between research and economy. In doing so the dissemination of the results is ensured.

5.2 Description of the plant components

5.2.1 Plant concept

For the research at TU Berlin a system consisting of quench and ESP were designed. The total system furthermore included the safety measures like oxygen monitoring and devices for supply and disposal of the operating media. Beth Filtration GmbH has produced and installed the following main components into the TUB gasification plant (positions in correspondence to Figure 6.11):
- Pos. 7 – Quenche,
- Pos. 8 – wet Electrostatic Precipitator and
- Pos 9 – High voltage unit (delivered by another vendor)
- Pos 10 Oxygen monitoring.

5.2.2 Dimensioning and design

The quench is installed downstream of the hot gas filter and upstream of the ESP. It is designed with a diameter of 260 mm and an effective height of 2.000 mm. The quench can be operated with 4 nozzles at different height-levels. With them the quench cools the gas from the gasifier from around 400℃ to 80℃ according to the specifications agreed upon in the consortium. As quench liquid water or RME (Rape Seed Oil Methyl Ester) can be used. The main function besides the quenching (cooling) effect is a precipitation of coarse particles and the condensation/dissolution of tar. The condensates pass through the inlet duct into the ESP. They are lead further towards the bottom of the ESP's filter housing where they can be drained out of the system. Together with the precipitated tar (and dust) from the ESP the tar condensates run through a hose into a waste liquid container (the waste liquid could eventually also be used as a substitute for RME).
The ESP consists of a cylindrical collecting electrode and a coiled discharge electrode. At the discharge electrode a high voltage of 60 kV (peak) and 50 mA (arithmetric) is applied.

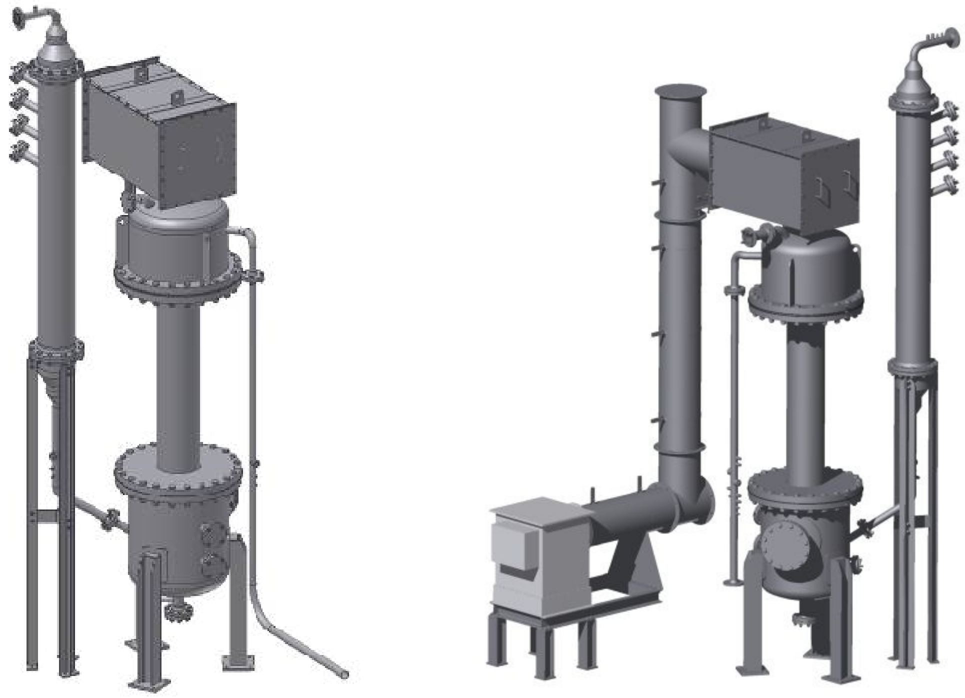


Figure 5.1: Design of quench and ESP (left) as built with HV-supply (right)

5.2.3 Installation work

After the design phase (creation of manufacturing drawing) and the selection of the manufacturer, the system was installed at TU Berlin. The individual steps are mentioned below:

- Installation of the steelwork
- Installation of the filter casing incl. all inner parts
- Alignment of the electrode system
- Installation of the quench
- Installation of the switch cabinet (low voltage)
- Installation of the HV-unit and the protective tube for high voltage connection
- Installation of the oxygen measurement (shut off the high voltage if the oxygen concentration is above 3 Vol.%)
- Installation of the valve table for water injection

- Installation of the RME supply unit
- Wiring of high and low voltage
- Connections of the valve table.

The individual steps of the installation are shown in the following images.

Figure 5.2: The bottom of the tar-ESP was set into position at TU Berlin

Figure 5.3:: Middle part of the ESP, Collecting electrode, Installation of the filter head

Figure 5.4: General view of the plant (ESP and Quench), incl. HV-unit, switch cabinet

5.2.4 Test runs

After installation all functions of the system had to be tested. According to the proposal the following parameters and their influence on separation efficiency and selectivity of the precipitation of individual tar components were planned to be examined:

- Quench liquids
  - Water
  - RME
  - (vegetable oil)
- Temperature
  - Gas temperature inside the ESP
  - Influence of the quench
  - Variations of the secondary voltage (high voltage)
  - Variations of the secondary current
  - Tar precipitation depending on the retention time
  - Particles loading of the gas
- Examination of special problems

  Deposits of individual tar components (like heteocyclic compounds from coal processing), cristallisation and condensation result in downtime and induce to an uneconomic operation of a commercial ESP. If also occurring in biomass gasification, solutions and improvements for such problem should also be identified.

First test showed that the relative small volume flow of 6 Nm³/h was not significantly heating up quench and filter system. These parts of the plant are not heated. So the resulting temperature of the ESP was near ambient temperature or just slightly 3 - 5°C above it. It took a couple of hours until the quench reached temperatures in the range of 50°C. A minimum of 35°C was set for the filter inlet temperature. To reach this temperature some hours during preheating of the system are needed. To shorten this time an additional heater was applied to one of the nozzle levels. Due to the fact that the temperature dropped in the filter nearly by itself from about 400°C at the inlet pipe to 50°C at the quench outlet it was decided not to use water as quenching liquid. This would have cooled the system even further down. So RME only was used for the tests.

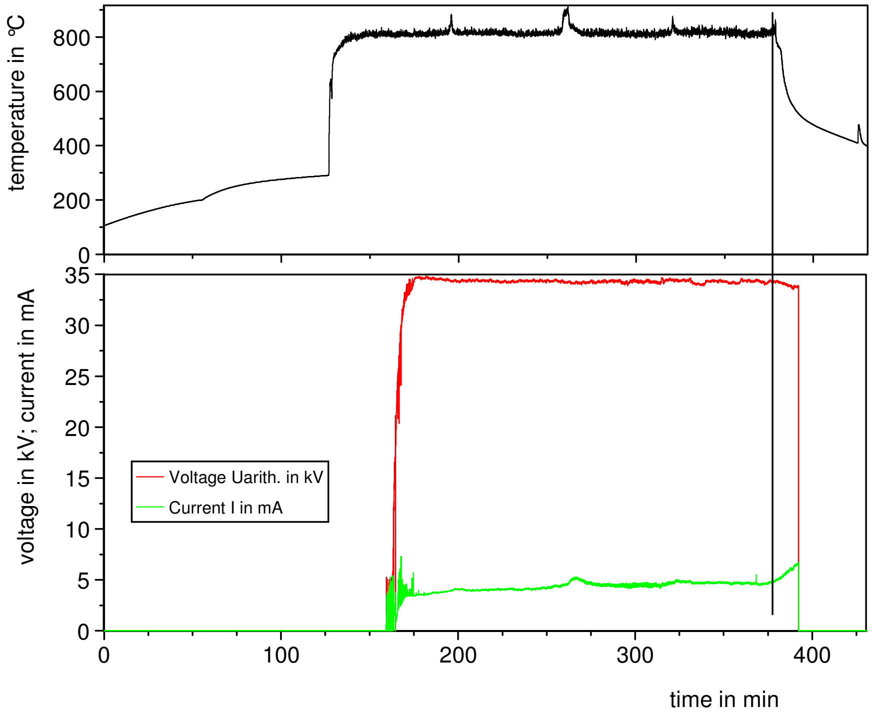


Figure 5.5: Filter current and voltage distribution during a consecutive run

In Figure 5.5 filter current and filter voltage are shown. They are quite uniform during the run. In the beginning the startup temperature of the filter was not reached so that the filter started up a bit after the gasifier produced gas. Tar and water in the gas and filter lead to spark over which could be heared. After a while the system ran calm and steadily through the duration of the run. At the end the reactor was set under nitrogen while the filter remained in operaion. The dottet line in the figure shows this. Under nitrogen the electric field behaves different from the normal operation conditions under gasification atmosphere.

5.3 Examination of tar separation with quench and ESP

The GC/MS was connected online with the system. Sample points were realized after the hot gas filter before entering the quenche and at the outlet of the ESP. In Figure 5.6 the concentration of selected tar species are shown. The value for naphthalene changed during the run whereas the other compounds showed less change. The first four measurements were done with the raw gas and then the sampling was switched to the point after the ESP. The last two values are downstream the ESP. It is obvious that the heavier tar compounds phenanthrene, pyrene but also fluorene are removed completely whereas naphthalene is reduced compared to the last raw gas measurements.

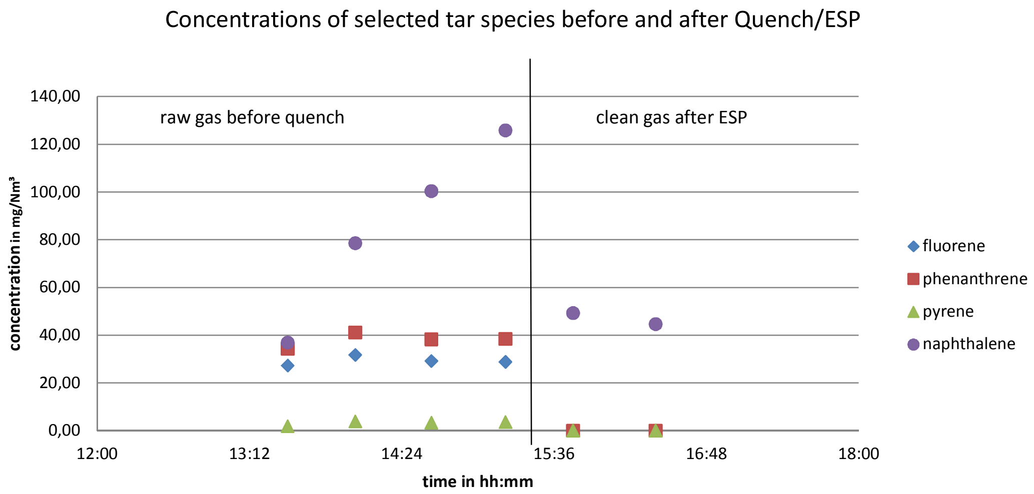


Figure 5.6: online GC/MS measurement results for selected tar species in the product gas; last two measurements were taken behind quench and ESP

When comparing with Figure 5.7 where benzene and naphthalene are shown the reduction is nearly not visible.

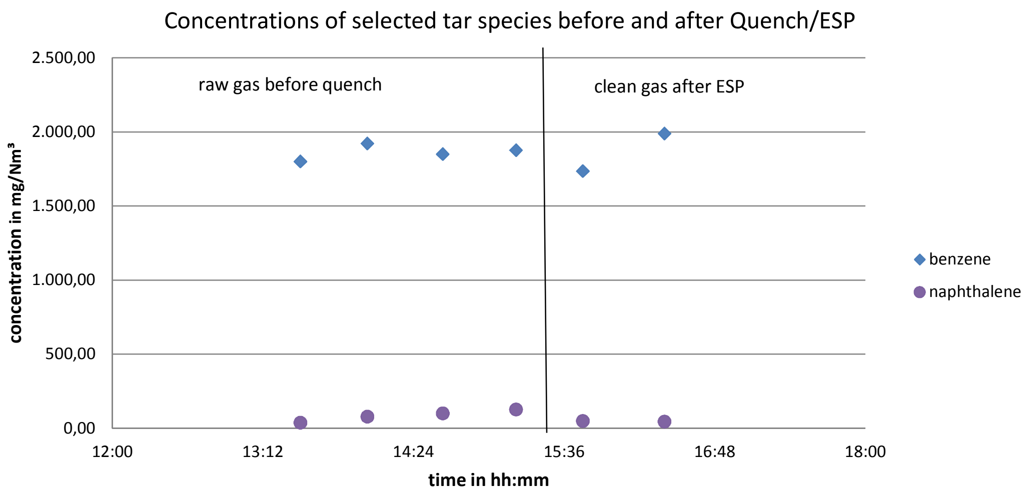


Figure 5.7: benzene (and naphthaline for comparison with figure 5.3)

The Ion Chromatograms in Figure 5.8 show more clearly what is meant. On the left hand side the peaks formed from the single ring aromatic compounds such as benzene, toluene, xylene, phenol or styrene can be found.

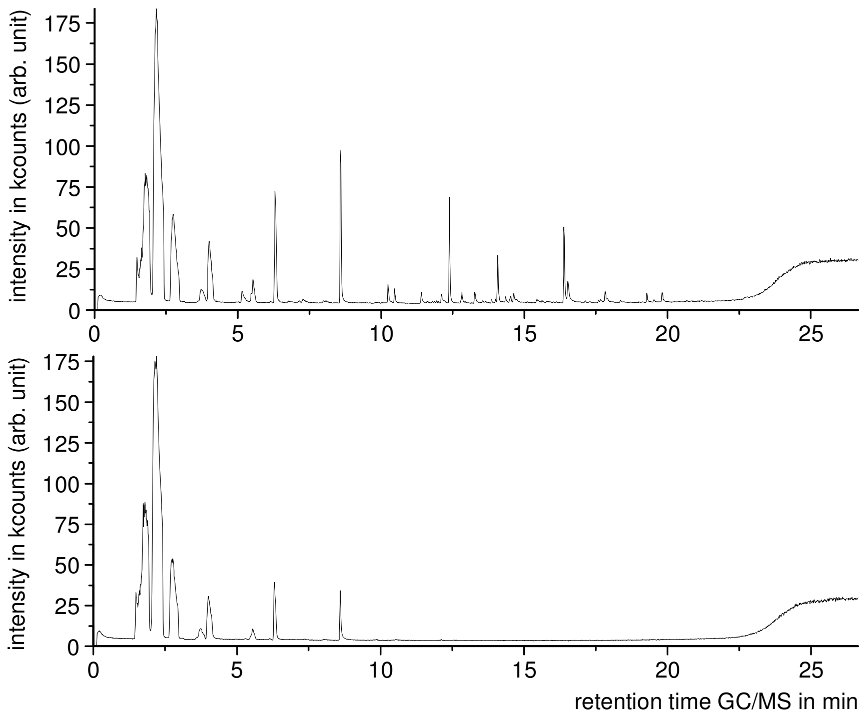


Figure 5.8: GC/MS ion chromatograms of measurements before (top) and after quench/ESP (bottom)

It is obvious that all heavy tar is removed from the gas. The last peak visible in the bottom spectrum is naphthalene. As shown in Figures 11 and 12 the level of the more complex PAH go to zero whereas naphthalene is just reduced. Benzene (the largest peak on the left hand side in the spectrum) is not effected at all by the system. The same is true for Toluene. At 5 minutes residence time the phenol peak is missing in the second spectrum as well. This could be due to dissolution of Phenol in condensing water.

Figure 5.9 shows the residue which is collected in barrels. It consists mainly of water. The tar is very little miscible with water and floats on top of the solution. Some water soluble compounds from the tar or the RME colour the water light brownish.

Figure 5.9: Tar-RME-Water mixture from ESP outlet

The oily phase was dissolved in acetone and then analysed with the GC/MS. Qualitatively most common tar species which can be detected by SPA, tar protocol or online GC measurements are present in the washing liquid. Figure 5.10 shows the reconstructed ion chromatogram of this analysis. The largest biodiesel peak at around 24 minutes is not measured. The higher tar compounds with more than three rings eluate together with the biodiesel components in the sample. Light tar compounds such as benzene and toluene as well as other abundant tar species were found.

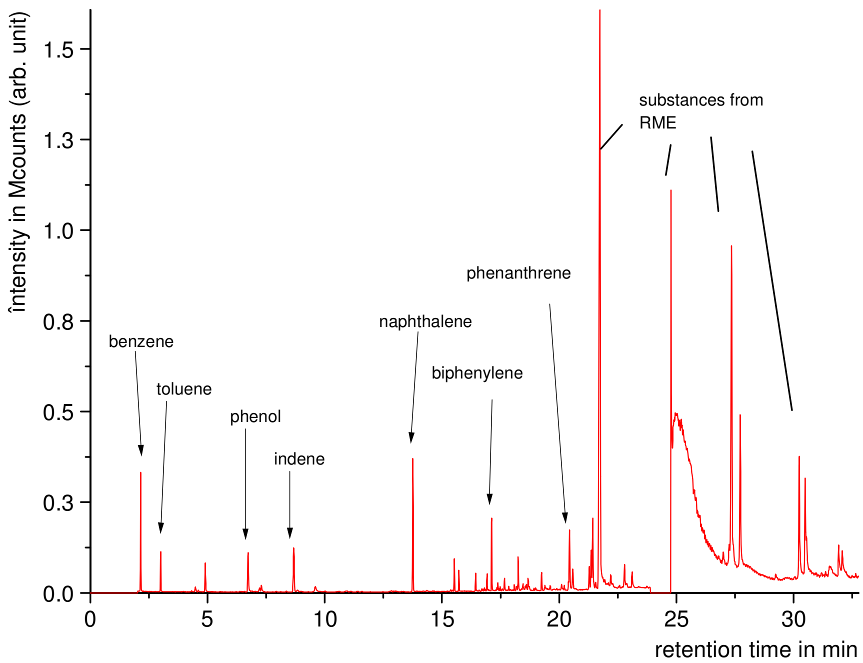


Figure 5.10: GC/MS Analysis of biodiesel (RME) from ESP containing tar

In order to determine tar removal efficiencies, the term tar has to be specified. Reported efficiencies of 99,4% removal [Sei/1928] were measured according to a method of Franz Fischer without specifying a source. Van Paasen et al. [vPa/2004] used the solid phase absorption method (SPA) and correlated the results to the 5 class tar model of ECN. Here no removal rate is given but numeric values for the individual classes. In this project we analysed tar species before quench and after ESP by online GC/MS: The values are fluctuating. Light aromatics are only little influenced by the system. As seen in Figure 5.7 also the light one-ring aromatic compounds are found in the RME sample from the ESP. A light reduction for benzene was observed ranging from 5 – 10 %. Naphthalene is not removed completely either but a reduction 80 – 95 % was observed. Water soluble compounds were removed very efficient as well as tar compounds more complex than the two-ring-PAH naphthalene. Heavy tar compounds are nearly completely removed (or not detected by GC/MS).

6 UNOTT – Mop Fan

A laboratory scale bubbling fluidized bed reactor was used for the studies of gasification of SRC willow chips and product gas cleaning. With continuous and reliable biomass feeding, the temperatures in the bed were evenly distributed in the main reaction zone. The mop fan cleaning unit was successfully applied to the cleaning of the product gas from gasification. Different fan rotating speeds and different flow rates of spray water were tested to optimise the performance of the mop gas cleaning unit. The particle removal efficiency with the tested mop was in the order of 50% without spraying water and as high as 90% if a small amount of water was sprayed on the mop fibres. The mop fan also showed a promising potential in removing water soluble species, e.g. N-species such as ammonia in the product gas, with the removal efficiency of more than 80% achievable.

6.1 Bubbling Fluidized Bed Gasifier (BFBG) and Mop Fan cleaning unit

A schematic of the bubbling fluidized bed biomass gasification system is illustrated in Figure 6., which consists of a bubbling fluidized bed reactor, a single screw biomass feeding unit, a cyclone for primary particle removal, a cooler, a downstream mop fan cleaning unit, a combustor, air supply/preheating and data acquisition devices. Silica sand in the range of 300-425μm is used as the bed material. SRC willow chips, with an approximate length of 1-12 mm, are used as biomass feedstock. Compressed air at ambient temperature is used as fluidization and gasification medium. Operating conditions are summarized in Table 6.1. Biomass feeding rate is controlled by changing the feeder motor frequency, resulting a various ER from 0.2 to 0.36 while the gasification and combustion air flow rates are kept as constant. Different mop fan rotational speeds and amount of spray water were tested to evaluate the performance of the mop fan cleaning unit.

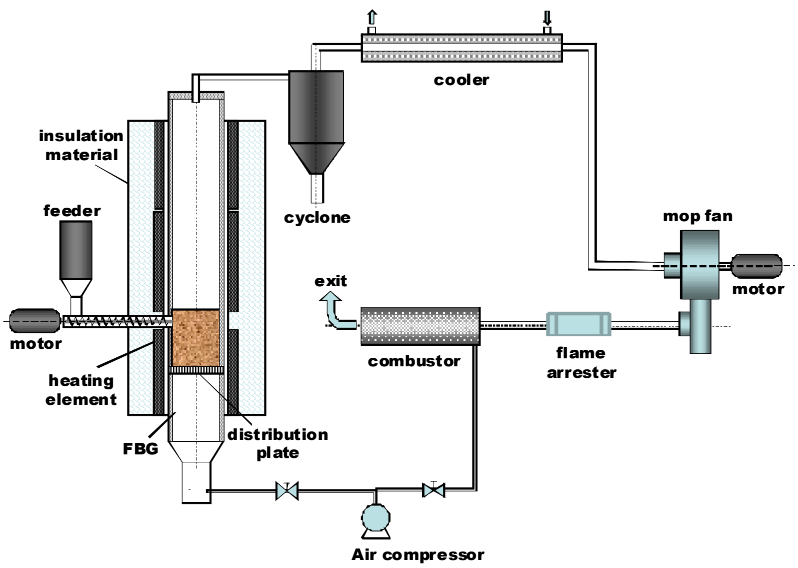


Figure 6.1: Schematic of bubbling fluidized bed gasifier and mop fan cleaning unit.

Table 6.1: Operating conditions used in gasification and product gas cleaning

Gasification air flow rate	48 litre/min		
Combustion air flow rate	150 litre/min		
Equivalent Ratio (ER)	0.2 – 0.36		
Zone temperature setup °C	660 lower	800 upper	850 combustor
Screw feeder motor frequency (Hz)	10/11.5/12.5/13.5/15		
Mop fan motor frequency (Hz)	10/15/20		
Mop fan spray water flow rate	0/0.5/0.75 litre/min		

On the left of Figure 6.2, it shows the schematic of mop fan cleaning unit. The dirty product gas containing particular matters, tar and chemical compounds enters the fan case, makes contact with the rotating mop fibres and is cleaned by the fibres within the case.

A small amount of water was sprayed on the surface of mop fibre to facilitate the particle and chemicals' removals. The performance of the mop fan cleaning unit in particle removal is evaluated by measuring particle loadings at both the inlet and outlet. A water trap bottle was also used to capture the particulate matters in the product gas. The flue gas composition at the exit of combustor was continuously measured by an online analyzer.

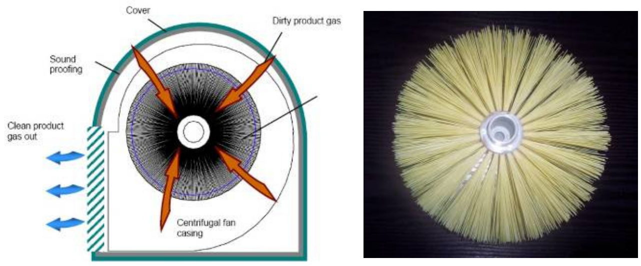


Figure 6.2: Schematic of mop fan cleaning unit and a real image of an example mop.

6.2 Biomass gasification results

Biomass feeding rate was calibrated when the screw feeder motor frequency was set to 10, 11.5, 12.5, 13.5 and 15 Hz. Figure 3 shows an acceptable linear relationship between biomass feeding rate and the motor frequency. By keeping the gasification flow rate at a constant value of 48 litre/min, the corresponding air ratio varies from 0.2 to 0.36. Figures 6.4 and 6.5 show the variation of temperature distribution at different axial locations from distributor plate after biomass feeding is started. The location of -5 cm is below distributor with less sufficient preheating which undergoes a decrease in temperature but begins to level off at around 20 min. The location of 150 cm is where the exit of the fluidized bed reactor locates. Except the above two locations, the temperatures in the main reaction zone, varying from 9 cm to 105 cm, had achieved fairly stable and homogeneous distributions. The average temperature in the reaction zone increased from ca. 700°C to ca. 750°C when ER was increased from 0.232 to 0.327.

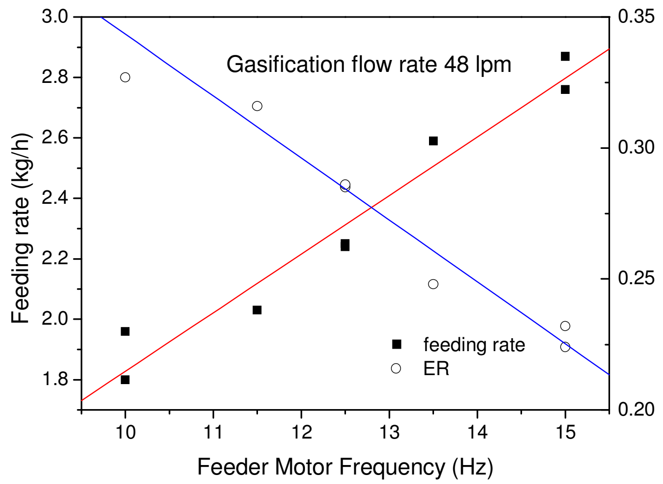


Figure 6.3: Biomass feeding rate and ER controlled by feeder motor frequency

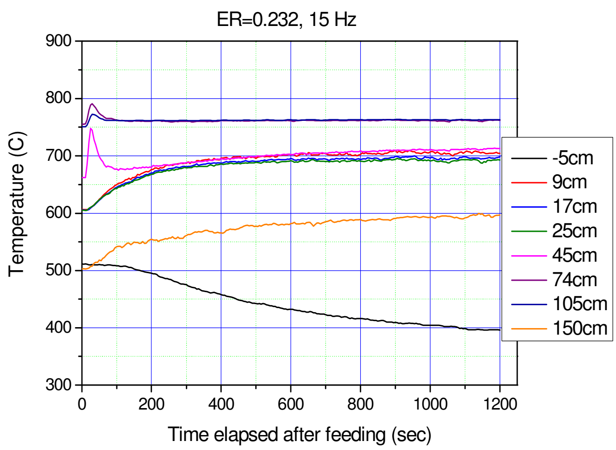


Figure 6.4: Temperature profiles at different locations from distributor, ER=0.232.

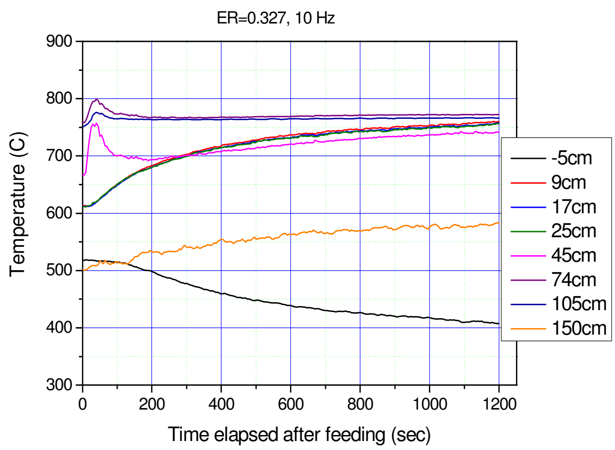


Figure 6.5: Temperature profiles at different locations from distributor, ER=0.327.

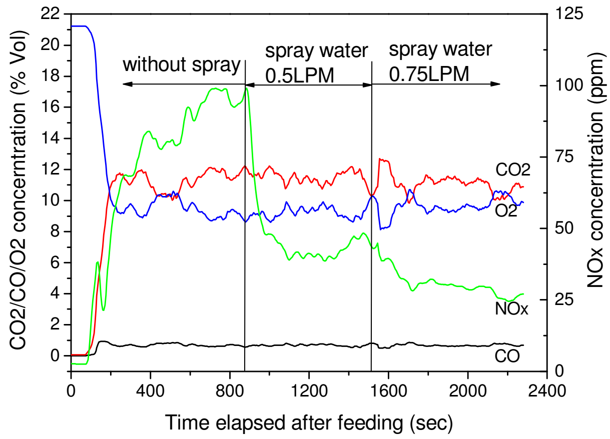


Figure 6.6: Flue gas composition when different amount of spray water is used.

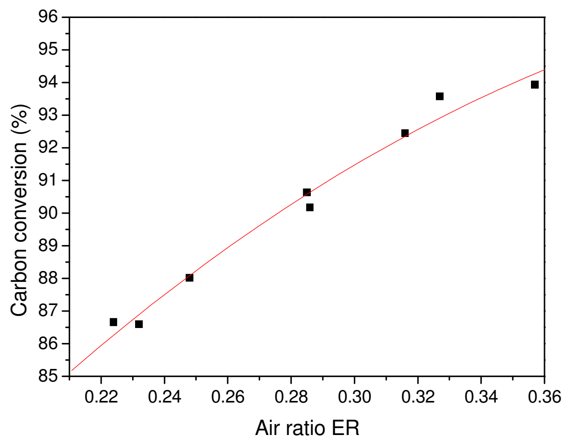


Figure 6.7: carbon conversion at different air ratios.

The composition of flue gas at the exit of the combustor was measured by online gas analyzers. Almost complete combustion of the product gas had been achieved within the combustor, which was indicated by the very low CO concentrations measured. Figure 6 shows the variations of O_2, CO_2 and NOx concentrations at the exit of the combustor during a period of gasification. Mop fan unit was running with different amount of spray water in different stages. It can be seen that the addition of spray water has a noticeable effect on NOx concentration as a large portion of water soluble N-species is believed to be absorbed and captured by the sprayed mop fibres. Further details will be discussed in section 6.3.
Figure 6.7 illustrates that carbon conversion has a variation from 86 to 94% at different gasification conditions when ER varies from 0.2 to 0.36. More results have shown that the yield of product gas is in the range of 2 – 3.2 m^3/kg.daf and the gross calorific value of the product gas varies from 3 to 6 MJ/m^3.

6.3 Evaluation of Mop Fan performance

A dust monitor was used to measure the particle loadings at the inlet and outlet of the mop fan cleaning unit. Since the device is sensitive to moisture content in the sampling gas, no spray water was used in these sets of measurements.

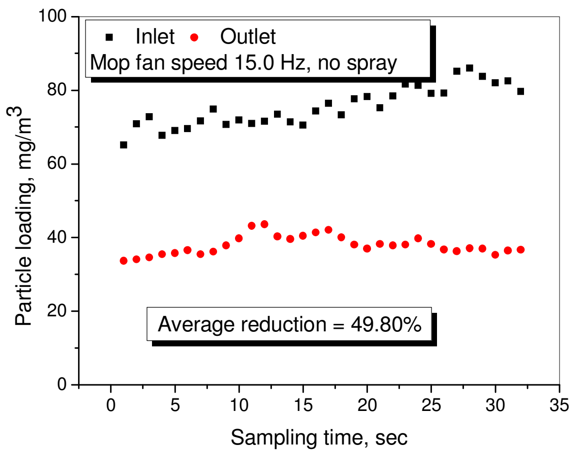


Figure 6.8: Particle removal efficiency by mop fan, fan speed 15.0, without spray water.

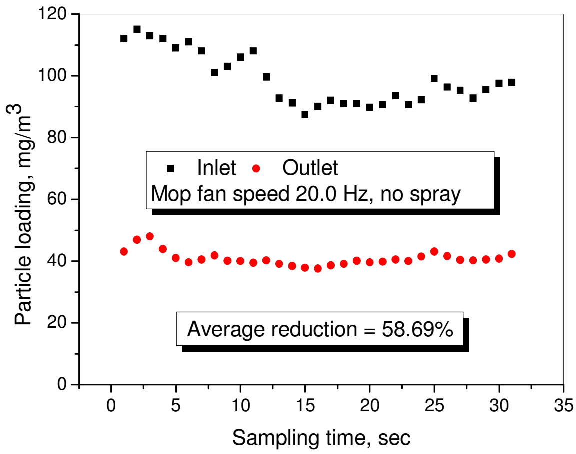


Figure 6.9: Particle removal efficiency by mop fan, fan speed 20.0, without spray water.

Figure 6. and 6.7 show the results when the mop fan speed was set to 15.0 and 20.0 Hz, respectively, without the spraying water. The particle removal efficiency was in the range of 50% to 60%. Increasing the mop fan rotational speed resulted in a slight increase in the particle removal efficiency.

When a small amount of water (0.5 litre/min) was sprayed on the mop fibres, the water bottle trapping method was used to capture the particulate matters in the sampling gas. Results are summarized in Table 6.2 which shows that a high particle removal efficiency of up to 90% has been achieved.

Table 6.2: Particle removal efficiency of the mop fan cleaning unit when a spray water of 0.5 litre/min is used

Run No.	RUN 1		RUN 2	
Sampling position	inlet	outlet	inlet	outlet
paper weight before filtering (g)	1.4529	1.4424	1.4403	1.4417
paper weight after filtering (g)	1.5197	1.4505	1.5044	1.448
particle mass captured (g)	0.0668	0.0081	0.0641	0.0063
particle concentration (mg/m^3)	477.1	57.9	457.9	45.0
particle removal efficiency (%)	87.9		90.2	

Figure 6.10 shows the average NOx concentration in the flue gas at different operating conditions. The use of the mop fan cleaning unit with or without water sprays resulted in a reduction of NOx, which is believed to be largely due to N-compounds (NH_3 etc.) of the product gas being trapped by the mop fan unit. By using the mop fan but without the water spray, an efficiency of 44.3% in removing N-species in the product gas was observed. With a small amount of spray water (0.75 litre/min), the efficiency of more than 80% in removing N-species was achieved by the mop fan cleaning unit.

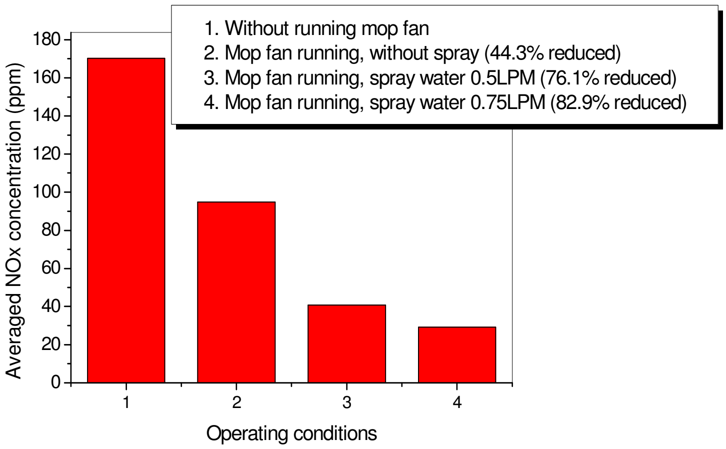


Figure 6.10: Removal efficiency of N-species by mop fan with different amounts of spray water

The mop fan cleaning unit has also been installed and tested on the gasification rig at TU Berlin. Figure 6.11 shows the location and integration of this unit in the whole gasification system and Figure 6.12 shows how this unit is connected between ESP and the combustor. Tests were performed with the proposed system setup as a whole. Gas cooler, quench, ESP and Mop-fan were operated together as gas cleaning unit. It was a successful operation. Due to limited time at the project end detailed analyses about the Mop-fan behaviour could not be finished. Especially the formation of droplets would be of interest. It was visible that the residues collected in the bin of the Mop-Fan contained compounds which were not very well water miscible. They were light coloured. They are assumed to be to a small degree to be residues from RME as well as the mono-aromatic fraction of the tar which in part passed quench and ESP. Further investigations on this subject would be necessary.

Also the positioning of the Mop-Fan as a second separation step in between quench and ESP seems suitable. Then a particle free gas containing nearly no droplets will be achievable. Furthermore the recycling of liquid streams in the process as a whole should be considered. As discussed in section 5 condensed water from the process would be available. If this would be of interest the droplet spectra for removal within the ESP has to be adjusted by fan rotation and liquid spraying. At the current overall system configuration the water consumption of the mop fan would have to be reduced to avoid a waste water problem.

The operation of the total system incorporating all proposed components was possible without experiencing larger problems. All components were functioning and operated successful.

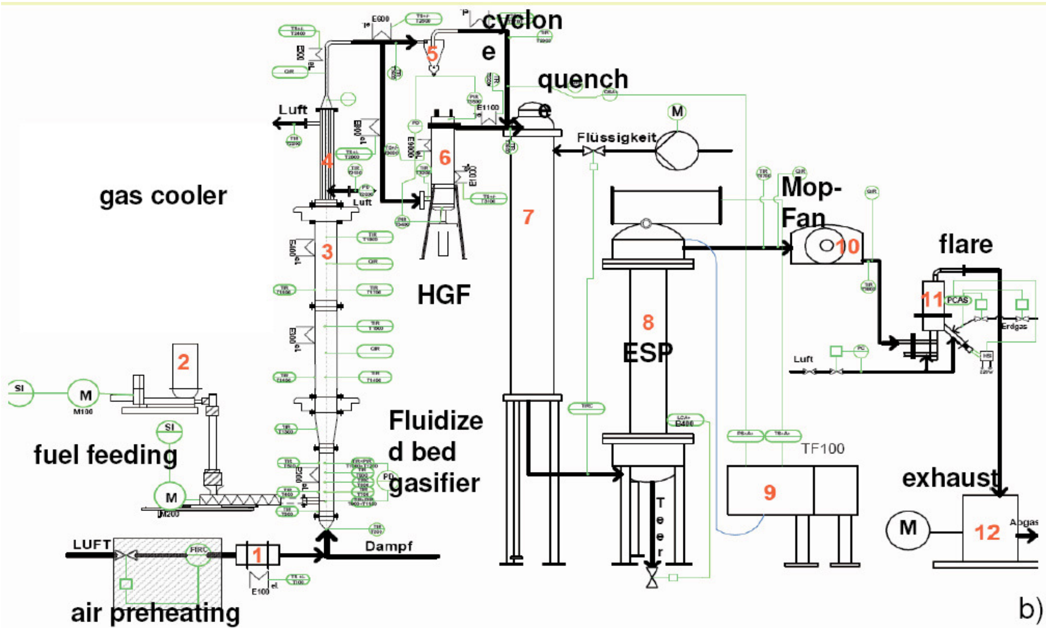


Figure 6.11: Mop fan unit integration in TUB gasification system

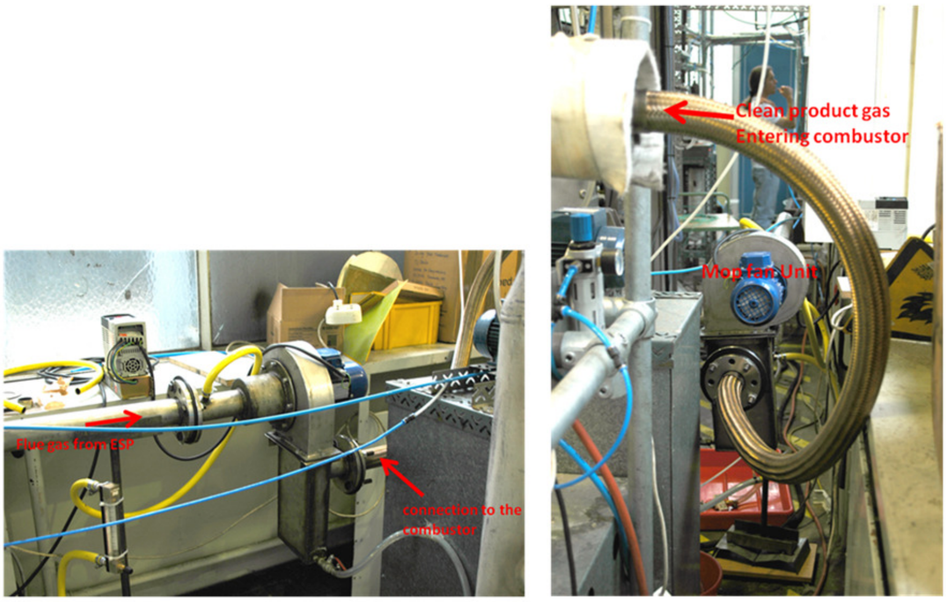


Figure 6.12: Photos showing the connection of mop fan unit between ESP and combustor

7 Summary

The results of the EMF project showed that proper gas cleaning and conditioning in smaller gasification plants can be achieved by combining innovative components. All of proposed components of the innovative gas cleaning and conditioning system including the gas cooler, the mop fan cleaning unit and the electrostatic precipitator (ESP) have been tested individually and collectively with biomass fluidized bed gasifiers. The mop fan cleaning unit has been thoroughly characterised at University of Nottingham (UNOTT), whereas the gas cooler, the ESP and the integrated system of the gas cooler, the mop fan and the ESP have been tested at Berlin Institute of Technology (TUB).

The mop fan cleaning unit was successfully applied to the cleaning of the product gas from the laboratory-scale (2 ~ 3 kg biomass/hr) biomass fluidized bed gasifier at UNOTT. Different fan rotating speeds and different flow rates of spray water were tested to optimise the performance of the mop fan gas cleaning unit. The particle removal efficiency with the tested mop was in the order of 50% without spraying water and as high as 90% if a small amount of water was sprayed on the mop fibres. The mop fan also showed a promising potential in removing water soluble species, e.g. N-species (ammonia etc.) in the product gas, with the removal efficiency of more than 80% achievable.

The gas cooler with structured tubes provided by ERK Eckrohrkessel GmbH has greater efficiency in heat exchange compared with the straight tube design. Preliminary qualitative analyses of residues in the heat exchanger indicated some minor deposition of tar compounds on the internal tubes. To quantify the fouling of the gas cooler, more operational time with the gas cooler on stream is needed.

Quench and ESP from Beth Filtration GmbH showed their capability for tar removal from the gas. The condensation of heavy tars takes place mainly within the Quench, whereas aerosols (droplets of water, tar and from the quenching medium (Rape Methyl Ester (RME)) or small particles are separated in the electric field of the ESP. Compounds which are present in the product gas in gaseous form or as vapour are almost unaltered by the electric field of the ESP. The quenching/washing unit before the ESP is necessary to bring down the temperature to a point where tar substances will condense on condensation nucleus. The removal of benzene, toluene, and xylenes (BTX) and parts of the naphthalene is strongly dependent either on a low temperature in the system or on an adequate washing medium. It seemed that not all RME was removed by the ESP. Improvement in the Quench design (nozzles, size and flow regime) and adaption of the gas velocity and residence time in the subsequent electric field could lead to better performance.

The testing of the integrated system has been carried out with the originally proposed component sequence (Gas Cooler, Quench, ESP and Mop Fan) with TUB gasification plant. The mop fan cleaning unit which uses a fine spray to enhance gas cleaning had led to problems with the pilot burner (which burns off the cleaned product gas) at the TUB plant. The amount of the fresh water used by for the mop fan cleaning unit had to be reduced significantly.

The results obtained with the project show that the originally proposed setup should be modified: following the gas cooler, the quenching unit is used to further reduce the gas temperature. In accordance with earlier findings in literature, a quenching system with oil or a tarry fraction of the collected quenching medium could be used to separate heavy tars from the gas. The waste water generated in the mop fan cleaning unit was an oily light coloured liquid with a strong solvent-like smell and could be used as the quenching medium. The mop fan cleaning unit can then be used for the removal of lighter tars by applying a compact device rather than large washing columns and finally the ESP is used to remove droplets of water and condensed tars from the gas.

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Mop-Fan und Elektrofilter: ein innovativer Ansatz zur Reinigung von Produktgasen aus der Biomassevergasung - EMF-Projekt

Deutsche Zusammenfassung

Die Ergebnisse der Messungen und Analysen im Rahmen des EMF Projekts zeigten, dass durch die Kombination von innovativen Anlagenkomponenten eine adäquate Gasreinigung bzw. Gaskonditionierung erreicht werden kann. Alle Komponenten des Systems, deren Kombination für das EMF- Projekt postuliert wurde - Gaskühler mit Strukturrohren (ip-power tubes) der Firma ERK Eckrohrkessel GmbH (ERK) aus Berlin, die Kombination von Quenche und Nasselektrofilter der Firma Beth (BETH) aus Lübeck sowie der Mop-Fan, ein Wäscher mit rotierenden Einbauten - wurden einzeln untersucht und im Verbund an der Tu Berlin betrieben und charakterisiert. Der Mop-Fan ist an der von der University of Nottingham, UK (UNOTT) entwickelt worden. Dort wurde er in diesem Projekt erstmals im Umfeld der Vergasungstechnologie eingesetzt und umfassend untersucht. Zum Projektende wurden Versuche im Gesamtverbund aller Anlagenkomponenten an der Vergasungsanlage der TU Berlin (TUB) durchgeführt.

Die Gaskühler der Firma Eckrohrkessel wurden direkt auf das oberste Feeboard-Segment des Wirbelschichtvergasers der TU Berlin angeflanscht. Damit konnte das heiße, partikel- und teerbeladene Produktgas sofort abgekühlt werden. Ziel der Untersuchungen war es, die schon in anderen Anwendungen gezeigten positiven Effekte auf den Wärmeübergang auch auf diese, schwierige Umgebung zu übertragen. Um eine Vergleichbarkeit herzustellen, wurden drei Wärmeübertrager mit verschieden stark strukturierten Rohren gefertigt und ein vierter mit Glattrohren als Referenz eingesetzt. In einer Ersten Versuchsreihe wurde der Wärmeübergang an den 4 Konfigurationen ermittelt. Dabei wurden auch kleinere Teerablagerungen auf den Oberflächen der Wärmeübertrager festgestellt. Die Apparate wurden als Gas-Luft-Wärmeübertrager im Gleichstrom betrieben. Diese Betriebsart wurde gewählt, um möglichst hohe Wandtemperaturen an den mit Produktgas in Berührung stehenden Teilen zu gewährleisten. Im Praxisbetrieb könnten die Apparate auch zur Überhitzung von Vergasungsmittel bei höherem Temperaturniveau verwendet werden. Für eine richtige Beurteilung der Ablagerungsproblematik waren die erreichten Betriebszeiten im Gas für die einzelnen untersuchten Apparate zu gering. Für eine zweite Versuchsreihe wurden die Temperaturmessstellen an zwei Wärmeübertragern verändert, um dieTemperaturen des einströmenden Gases genauer zu ermitteln. Die Messergebnisse waren qualitativ aussagekräftiger als die der ersten Versuchsreihe und auch in besserer Übereinstimmung mit berechneten Werten. Es zeigte sich in den Untersuchungen deutlich, dass die Strukturrohre den Wärmeübergang sehr positiv beeinflussen und dass diese Technologie gute Möglichkeiten zum Einsatz in Vergasungsanlagen bietet.

Die Versuche mit Quenche und Elektrofilter zeigten, dass Teer mit einem solchen System erfolgreich abgeschieden werden kann. Das System wurde in der Anlage nach einem Heißgasfilter betrieben. Damit konnte die Teerabscheidung ohne den Einfluss von Partikeln untersucht werden. Es zeigte sich, dass die Teerabscheidung stark vom Temperaturniveau der Apparate und vom Wirken der Quenche abhängig ist. Leichtflüchtige kondensierbare Komponenten wie Benzol, Toluol oder Xylol (BTX) werden kaum abgeschieden, wogegen nahezu alle Teerinhaltsstoffe im Gas mit Molekulargewichten größer als dem des Naphthalins (128) nahezu vollständig aus dem Gas entfernt wurden. Phenol, das wasserlöslich ist, wurde vermutlich zu einem großen Teil in der Kondensatphase des sich aus dem Gas niederschlagenden Wassers gelöst. Andere monoaromatische Verbindungen im Gas wurden in ihrem Ge-

halt reduziert. Die Ablagerungsproblematik vieler Holzgas-BHKW könnte mit individuell angepassten Quenche-Nasselektrofilter-Systemen wesentlich entschärft werden. Dem stehen allerdings, insbesondere bei kleinen Anlagen, die vergleichsweise hohen Investitionskosten für die Hochspannungseinheit sowie für das Sauerstoff-Überwachungssystem (Explosionsschutz) gegenüber. Auch muss im Weiteren geklärt werden, wie das sich gut in zwei Phasen trennende Gemisch aus RME (Quenchmedium)- Wasser und Teer (Kondensate) zu entsorgen ist. Ansätze wie die von ECN oder früher von Lurgi im Bereich der Kohlevergasung trennen schweren Teer und wasserreiche Fraktionen im System separat ab. Eine Optimierung der Quenche oder des Quenchmediums z. B. durch Rezirkulation eines Teils des abgeschiedenen Mediums müssten noch eingehender untersucht werden, um mehr leichtflüchtige Komponenten in Lösung zu bringen und diese letzendlich im elektrischen Feld des Filters abzuscheiden.

Das Mop-Fan Gasreinigungssystem wurde an der UNOTT erfolgreich an einem stationären Wirbelschichtvergaser im Labormaßstab (2-3 kg Biomasse/h) eingesetzt. Es wurden die Einflüsse auf die Gasreinigung bei verschiedenen Drehgeschwindigkeiten des Rotors und veränderlichen Durchflussraten des Spülmediums (Wasser) untersucht. Die Effizienz der Partikelentfernung aus dem Gas wurde ohne aufgesprühtes Wasser mit 50% ermittelt. Mit Spülmedium wurden Abscheideraten bis zu 90% erreicht. Die Abscheidung wird dadurch erreicht, indem das Gas ähnlich dem Strömungsfeld einer Kreiselpumpe den Mop-Fan durchströmt wobei die Partikel durch die sich schnell bewegenden Fasern in ihrer Bewegung beeinflusst werden. Dieser Effekt wird verstärkt, wenn ein flüssiges Medium, in diesem Falle Wasser, zum Einsatz kommt. Das Medium fließt als Film auf den Fasern und wird durch die Fliehkräfte nach außer befördert. Dabei werden Partikel durch den intensiven Austausch an die Flüssigphase gebunden und an der Gehäusewand abgeschieden. Der Mop-Fan zeigte auch vielversprechendes Potenzial bei der Abscheidung wasserlöslicher Gasinhaltsstoffe wie z. B. Ammoniak, der in Produktgasen der Vergasung häufig zu finden ist. Durch indirekte Messungen der NOx-Konzentration in der nachgeschalteten Brennkammer konnten hierbei Reduktionsraten bis zu 80% ermittelt werden.

Die Untersuchung des gesamten integrierten Systems erfolgte gegen Projektende an der Vergasungsanlage an der TU Berlin. Die Anlagenkomponenten konnten in der ursprünglich geplanten Konfiguration zusammen betrieben werden. Funktionalität und Zusammenspiel konnten erfolgreich demonstriert werden. Trotzdem zeigte sich Verbesserungspotenzial zum ursprünglichen angedachten und realisierten Setup. Der Mop-Fan verbraucht in der untersuchten Konfiguration relativ viel Spülwasser. Er könnte zwischen Quenche und Elektrofilter als Abscheider positioniert werden. Damit könnte hier der Stoffaustausch hinsichtlich der Abtrennung leichtflüchtiger und auch wasserlöslicher Gaskomponenten verbessert werden. Die Tropfenabscheidung erfolgt dann im elektrischen Feld. Dann wäre auch der hohe Spülmediumsverbrauch unproblematisch, sofern Rezirkulat eingesetzt wird. In der getesteten Anordnung und Betriebsweise war der Wasserverbrauch des Mop-Fan zu hoch für eine praktikable Anwendung auch wenn das Gas weiter aufgereinigt werden konnte. Hier liegt noch entscheidendes Potenzial in der weiteren Verbesserung des Gesamtsystems.