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TAR REMOVAL WITH A WET ELECTROSTATIC PRECIPITATOR (ESP); A PARAMETRIC STUDY

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ABSTRACT: The ElectroStatic Precipitator (ESP) removes dust and tar droplets very efficiently from biomass product gas. Dust was removed for more than 99%. The tar dewpoint was reduced from 130°C to 21°C, which is sufficient for the application of the product gas in a gas engine. Tar removal is not sensitive to the voltage or fluctuations in the gas residence time . The voltage was varied between 28 to 37 kV_{arith} and the gas residence time between 4 and 11s. Fouling of the ESP collector plates was negligible, which was concluded from visual inspection after 200 hours of operation. A reduction in the residence time reduces the size of the ESP and has a significant impact on the investment costs of the ESP.
Keywords: electrostatic filter, tar removal, circulating fluidised bed (CFB)

1 INTRODUCTION

Tar in product gas from a biomass gasifier can easily block filters, plug process equipment and hamper the operation of prime movers that use the gas (e.g. a gas engine). Therefore, tar removal is an important task for the gas cleaning section of a biomass gasification plant. Wet gas cleaning has successfully been applied for electricity generation with gas engines downstream an updraft gasifier in Harboore, a downdraft gasifier in Wiener Neustadt and the circulating fluidised bed gasifier at ECN [1,2].

A wet ESP (ElectroStatic Precipitator) forms an important part of the wet gas cleaning at ECN. The ESP captures tar-aerosols and dust fines and protects downstream equipment from tar related fouling. At ECN the ESP is operated isothermally at ambient temperature, constant voltage and gas residence time.

The basic principle of a wet ESP is simple. Gas is ionised upon passing between a high voltage electrode and an earthed (grounded) electrode. The ions are produced in a corona discharge and attach themselves to dust particles or droplets of tar and water. Particles and droplets become charged and are attracted to the grounded electrode due to the electric field. The precipitated dust and droplets flow to the bottom of the ESP where they are collected.

The collection efficiency is influenced by many process parameters like temperature, pressure, ESP voltage, gas flow rate and composition, including the tar droplet and dust load. Most variables are determined by the composition and feed rate of the biomass feedstock and the applied conditions in the gasifier and equipment upstream of the ESP.

The objective of the present parametric study was to optimise (*i.e.* minimise) the investment costs of the ESP without influencing the technical reliability. The investment costs depend on the size of the ESP and thus on the gas residence time in the ESP. The technical reliability depends on the influence of the ESP performance on fluctuations in process parameters. The ESP is performing well when downstream unit operations are protected against fouling related to dust and tar condensation.

2 WET GAS CLEANING AT ECN

A simplified process flow diagram of the wet gas cleaning configuration at ECN is given in Figure 1. Upstream of the wet gas cleaning, most particles are removed by a cyclone and the product gas is cooled down to 300-350°C. In the wet gas cleaning, the product gas is further cooled down to 20-30°C and tar partly condenses in a quench scrubber. Droplets of condensed tar and water formed in the scrubber are removed together with fine dust particles in the wet ESP. Downstream of the ESP, ammonia is removed from the product gas with a scrubber to prevent production of fuel-NO_x in the gas engine [2].

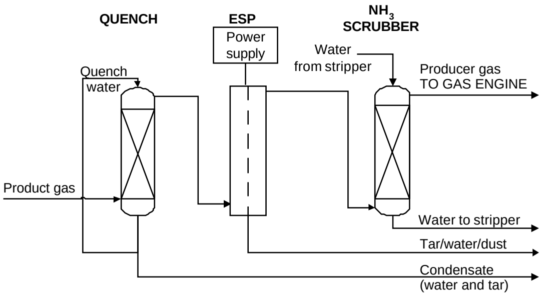

Figure 1: Wet gas cleaning at ECN

3 TAR CONDENSATION

Knowledge about the condensation of tar is indispensable for the reliable operation of a biomass gasification process and for the judgement of the performance of tar removal units like the wet ESP.

ECN has developed a model for the calculation of the temperature at which tar of a given (measured) composition starts to condense. This temperature is called the *tar dewpoint* and is a thermodynamic property. In other words, the tar dewpoint is the temperature at which the total partial pressure of a compound or a mixture of compounds (like tar) equals the saturation pressure. Once the actual process temperature drops below the thermodynamic dewpoint, the compound or mixture of compounds can condense out. It does not mean that condensation will always happen. Kinetics may be too slow in which case the gas becomes over-saturated.

The dewpoint model of ECN includes vapour/liquid equilibrium data for the tar compounds in the product gas from a downdraft or fluidised bed gasifier. The calculation is based on ideal gas behaviour. Raoult's law is applied for the calculation of the tar dewpoint for a mixture of tar compounds, using the vapour pressure data of the individual compounds. A simplified version of the model is available on the internet at www.thersites.nl.

The model has been validated with real product gas from the ECN laboratory scale bubbling fluidised bed gasifier (WOB). The model predicted the tar dewpoint with an accuracy of 3°C. Herewith, the tar dewpoint model is a useful tool for the prediction of the temperature at which a measured tar mixture starts to condense. In this paper, the tar dewpoint is used for the judgement of the ESP performance.

4 PARAMETRIC STUDY

A parametric study has been performed to assess the influence of ESP operating voltage and gas residence time on the ESP performance. The ESP performs well when the tar dewpoint at the outlet of the ESP equals the gas temperature.

4.1 Experimental conditions

The feedstock for the gasifier was composed of a mixture of demolition wood pellets and chicken manure. The gasifier was operated at constant temperature and air to fuel ratio. The average process conditions in the gasifier as well as the average concentrations of the main components are given in Table I.

Table I: Process conditions and gas composition.

Operating conditions		
Chicken manure	kg/h	26.2
Wood pellets	kg/h	52.3
Air	m_n^3/h	92.7
Temperature gasifier	°C	852
Gas composition (dry basis)		
CO	vol%	12.9
H_2	vol%	8.8
CH_4	vol%	2.9
C_2H_4	vol%	1.1
C_2H_6	vol%	0.1
CO_2	vol%	15.5
N_2	vol%	59.3
Benzene	ppmv	1272
Toluene	ppmv	106

Gas analysis was performed with micro-GCs at the outlet of the ESP. Dust and tar measurements were performed at the inlet and outlet of the ESP. Tar measurements were done according the SPA method [3]. Dust measurements were performed by drawing 0.1 to 0.2 m_n^3 of gas through an absolute filter, which was heated to 250°C. The dust concentration can be calculated from the difference in filter weight before and after sampling and the gas volume drawn through the filter.

Table II: Experimental matrix for the parametric study

Test run	Residence time [s]	Gas velocity [m/s]	Current [mA]	Voltage [kV_{arith}]
1	7.7	0.4	1.5	35
2	3.9	0.8	1.5	34
3	11.4	0.3	3.8	36
4	5.4	0.6	2.0	34
5	5.4	0.6	0.5	28
6	5.4	0.6	1.0	30

The parametric study was performed in six test runs. The experimental matrix is given in Table II. The current was measured during the test runs. The gas residence time was varied by changing the gas flow rate and the active cross-section of the ESP.

The tar and dust concentrations at the inlet of the wet ESP are given in Table III. The total tar concentration fluctuated between 0.9 and 2.2 g/m_n^3. The tar dewpoint of the tar samples ranged from 111°C to 148°C.

Table III: Tar concentrations at the ESP inlet (dry basis).

Test run	Total tar [mg/m_n^3]	Dewpoint [°C]	Dust [mg/m_n^3]
1	2224	148	101
2	1432	111	d.
3	1886	135	d.
4	1035	125	202
5	920	123	286
6	930	131	641

d.: disturbed by tar deposition.

The tar compositions at the ESP inlet are given in Figure 2, with tar compounds grouped into classes. The classification system is based on the tar properties like water solubility and tar condensation temperature [4]. Class 1 tars are too heavy to be measured with the SPA method, and are, therefore, not included in our results. Class 2 tars are aromatic compounds with hetero atoms *e.g.* oxygen and nitrogen atoms. Most of them have a high water solubility. Class 3 tars are light compounds with 1 aromatic ring. These tar compounds are volatile and do not contribute to tar related problems. Class 4 tars are compounds with 2 or 3 aromatic rings and class 5 tars are compounds with 4 to 7 aromatic rings. Both class 4 and class 5 tars (partly) condense when the gas is cooled down to 20°C.

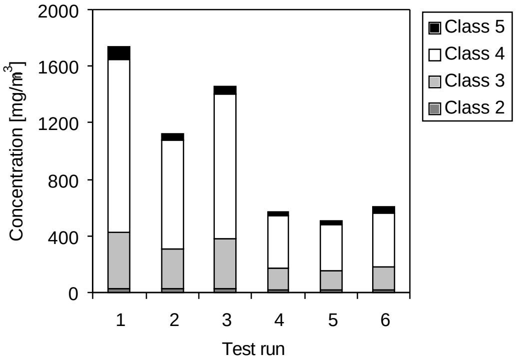

Figure 2: Tar composition at the ESP gas inlet.

The total tar concentrations reported in Table III are the sum of all tar compounds that can be measured with a GC, excluding toluene. Besides the class 2 to 5 tar compounds, the total tar concentrations include also tar compounds that are measured with a GC, but not identified.

4.2 Gas residence time

The relation between the ESP performance and the gas residence time was determined for residence times between 4 and 11s at a high voltage of approximately 35kV_{arith}. At normal gasifier operating conditions, the gas residence time in the ESP is approximately 10 s. Three of the four hexagonal tubes of the ESP were (gas tight) closed and the central wires were removed to decrease the residence time. Since the gasifier was operated at constant conditions, larger residence times were obtained by using only part of the product gas. The gas flow rate was set with a booster fan downstream the ESP.

The experimental results are given in Table IV. Typically, all condesable tars are removed and the tar dewpoint at the ESP oulet equals the gas temperature of 21°C. The total tar concentrations were approximately 700 mg/m_n^3 (Figure 3), and hardly dependent on the total inlet concentrations. Dust was removed essentially completely. The execption is Run 1, which was caused by the fact that the ESP was still in the start up phase and not running stably. Class 5 tars were only removed for 85% and dust for 90%. The presence of heavy class 5 tars in the form of tar droplets in the gas at the ESP outlet, result in a large difference between the tar dewpoint and the actual gas temperature of approximately 20°C.

Table IV: Tar and dust concentrations at the ESP outlet for different gas residence times.

Test run	Residence time [s]	Total tar [mg/m_n^3]	Dewpoint [°C]	Dust [mg/m_n^3]
2	3.9	636	21	3
4	5.4	620	21	0
1	7.7	732	91	10
3	11.4	863	21	0

The total tar concentrations are dominated by light tar compounds like xylene (class 3 tar) and indene (class 4 tar). The contribution of naphthalene to the total tar concentration was relatively low (40 to 80 mg/m_n^3). The heavy class 5 tars are completely removed and the class 4 and class 2 tars are partly removed at both high and low gas residence times. The class 3 tars remain in the product gas, as is expected based on their vapour pressure.

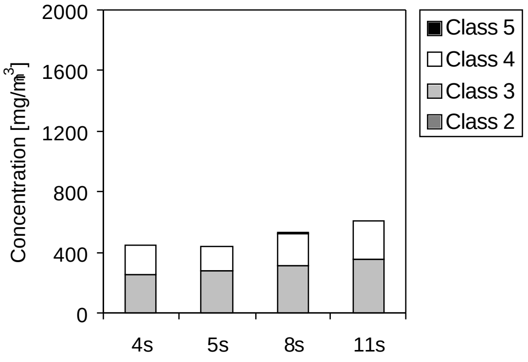

Figure 3: Tar composition at the ESP gas outlet at different residence times and 35 kV_{arith} high voltage.

From these experimental results it can be concluded that at a gas residence time of approximately 4s, downstream equipment is protected against tar related fouling, provided that the product gas temperature does not decrease downstream the ESP.

4.3 Voltage

The relation between the ESP performance and the the voltage was determined between $28kV_{arith}$ and $34kV_{arith}$ at a constant gas residence time of 5.4 seconds. The voltage is the main parameter for the ESP electric field that is the driving force for charging and collection of the tar droplets and dust particles. The electric field may be influenced by many (fluctuating) process parameters in a biomass gasification process. Fluctuations in the electric field, induced, e.g. by changes in process parameters like gas flow rate, gas composition, tar and dust load, may influence the collection efficiency for particles and tar droplets.

Normally, an ESP is running close to the maximum voltage allowed by breakdown discharges. The corona inception voltage[1] determines the minimum voltage for an ESP. The collection efficiency drops significantly when the ‘average’ voltage decreases under the corona inception voltage.

In the test runs the minimum voltage was determined by a set point in the power supply for the protection of the ESP. Therefore, the lowest voltage applied was above the corona inception voltage.

The experimental results are given in Table V and Figure 4. The tar dewpoint at the ESP outlet was approximately 20°C, independent of the voltage. The total tar concentration at the outlet was approximately 550 mg/m_n^3. Dust was completely removed.

Table V: Tar and dust concentrations (dry basis) at the ESP outlet for different voltages.

Test run	Voltage [kV_{arith}]	Total tar [mg/m_n^3]	Dewpoint [°C]	Dust [mg/m_n^3]
5	28	592	21	1
6	30	465	18	0
4	34	620	21	0

The total tar concentrations were mainly determined by light tar compounds like indene and xylene. The heavy class 5 tars were completely removed and class 4 tars were partly removed. Remaining class 4 tars

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[1] The corona inception voltage is the threshold voltage for corona discharges in the ESP.

were mainly determined by indene and approximately 40 mg/m_n^3 of naphthalene. Also class 2 tars were partly removed in the ESP, the remainder being determined by approximately 10 mg/m_n^3 of isoquinoline.

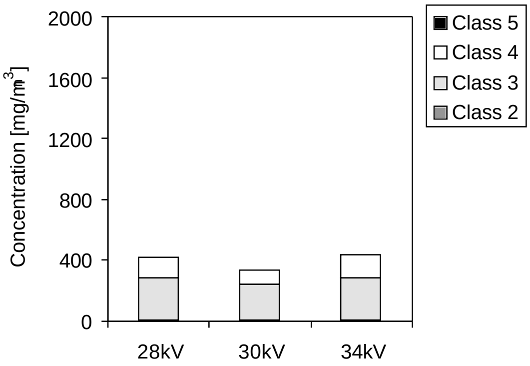

Figure 4: Tar compositions at 28 to 34kV$_{arith}$ voltage and 5 s residence time.

The ESP removes dust and tar droplets very efficiently at voltages between 28 and 34 kV$_{arith}$. The dust concentration and tar dewpoint of 20°C are sufficiently low for application of the product gas in a gas engine and the protection of downstream equipment against tar and dust related fouling. The flexibility in voltage improves the reliability of the ESP.

4.4 Fouling

The ESP is operated in the wet mode to prevent fouling of the collector plates with tar. In the wet ESP, tar and water droplets are both removed from the gas stream together with fine dust. Water and tar droplets stick to the collector plates, and flow to the bottom of the ESP due to gravitational forces. The tar-water mixture is collected in the bottom and can be drawn off via an S-trap.

At normal operating conditions, water droplets from the quench scrubber are carried over the top and enter the ESP. When too little water is carried over, additional water can be sprayed into the product gas, with the spray nozzle at the entrance of the ESP. This allows control of the tar-water ratio, an important parameter in the operation of the ESP.

After 200 hours of operation, the ESP was opened for visual inspection. Although the ESP had captured approximately 25 kg of tar, the ESP remained relatively clean. Rust was visible on the electrode configuration, which indicates that no tar layer was formed on the electrodes. Naphthalene crystals, slightly brownish due to captured heavy tars, were visible at the cold surfaces at the gas inlet and outlet of the ESP. The naphthalene deposition was a consequence of an ESP design choice, *i.e.* surfaces at the ESP gas inlet and outlet were relatively cold due to low ambient temperatures at the date of the test (0°C) and the absence of insulation around the ESP.

As a conclusion, the ESP collector plates remain clean and the tar-water mixture could be drawn off via the S-trap. The ESP must be insulated to prevent naphthalene deposition in the gas inlet and outlet.

5 ECONOMICS

The success for the application of the ESP is determined by its technical performance, and maybe even more important, by the economical perspectives. The economical feasibility is determined by many factors and is always a balance between the total manufacturing and capital investment costs and the revenues generated in the process.

In Table VI the ESP investment costs and costs for oxygen measurements (a safety measure) are given for biomass gasification plants with capacities of 2.2 MW$_{th}$ and 10 MW$_{th}$, respectivily. The installation costs (including start-up costs) are given as a percentage of the investment costs and with The Netherlands as location. The cost data can be used for cost estimates on conceptual design level.

Striking is the small difference between investment costs for an ESP with a capacity of 800 and 3600 m_n^3/h. The investment costs of the ESP are dominated by the costs for the power supply and for the vessel. The costs for the power supply are fairly constant due to the low energy use of approximately 800 and 3100 W, respectively. Therefore the investment costs only depend on the size of the vessel. When the gas residence time is doubled than the investment costs increases with 4% or 13%. A four times higher gas flow rate results in an 11% to 21% increase in investment costs. The prices are given for mild steel. When stainless steel is used than the investment costs increases with 10% to 20%, depending on the world market price of the alloying parts.

Table VI: ESP Investment and additional costs

Gas flow [m_n^3/h]	Residence time [s]	Investment [k€]	Installation & start up %of Inv.	Oxygen meas. [k€]
800	4	135	27%	50
800	8	140	26%	50
3600	4	150	25%	50
3600	8	170	23%	50

6 CONCLUSION

The ESP efficiently removes dust and condensible tar droplets from product gas. A gas residence time of 4 s was enough for total tar removal. The internal of the ESP is not poluted. The cleaned product gas is on specification to protect downstream equipment against tar and dust related fouling and for firing a gas engine. Investment costs for a ESP with a capacity 2.2 MW_{th} and 10 $MW_{th}$are 61 to 15 €/kW_{th}, respectively. Herewith is the ESP a very attractive solution for combined tar aerosol and dust removal.

ACKNOWLEDGEMENTS

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