Model Calculation of Negative Wire-Cylinder Corona Discharge Properties in Humid Synthesis Gas

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1 Summary / Abstract:

For the final clean-up of the synthesis gas produced from a small scale biomass gasification plant having a gas flow rate of 35 kg/hr a wet ESP has been designed and tested. Design was supported by model calculations of the current-voltage characteristics of the wire-tube precipitator. Electronic and ionic properties of multi-component gas mixtures were evaluated from cross section data using a Boltzmann code and ion mobility formulas. Both for synthesis gas and humid air simulated corona inception voltages exceeded measured ones for about 20-30 %, and simulated currents were 20-30 % too low. That measured corona inception voltages are too low can be attributed to the surface roughness of the wire used. Electrons contributing to the current in the drift region of the corona are assumed to be the reason for the larger currents observed in the experiments.

2 Introduction

Small scale biomass gasification plants combined with a gas engine and a generator may be an interesting option for decentralized energy supply in rural areas of developing countries. However, the application of a gas engine requires clean syngas containing no more than 50 mg/Nm^3 of particulate matter and tar [1]. Thus gas cleaning is essential in such a plant. Wet electrostatic precipitation is a well known gas cleaning technology for gasification plants allowing reducing particulate matter and condensed tar concentrations in synthesis gas efficiently [2]. In this conference contribution a biomass gasification plant consisting of a fixed bed draft down gasifier having a biomass capacity of 35 kg/hr, a hot gas cyclone as a first cleaning stage removing most of the initial ash content, two water scrubbers reducing particulate matter to about 170 mg/Nm^3 and tar to 50 mg/Nm^3, a wet electrostatic precipitator (ESP) as a final cleaning stage and a blower providing the air flow through the plant is considered.

For the design of electrostatic precipitators (ESP) the knowledge of corona discharge initiation voltages and the current-voltage characteristics is desirable. For air engineering formulas can be found in textbooks [3]. Because for synthesis gas this information is not available, we evaluated the electrical characteristics of a wire-tube precipitator by means of numerical simulation. Model results were compared to experiments performed at a wet ESP consisting of a bundle of three parallel tubes each having a length of 2 m and an inner diameter of 52 mm and centered stainless steel wires having a diameter of 1 mm. Due to the operation conditions of the biomass gasification plant the flowing syngas is assumed to have a pressure of 86.2 kPa (ambient pressure reduced for the pressure drop at the draft down gasifier and the first three cleaning stages) and a temperature of 40 °C. In experiments performed with air the pressure and temperature were 91.2 kPa and 30 °C, respectively.

3 Corona Discharge Initiation Voltage

The approach applied for evaluation of the corona initiation voltage is based on a combination of electrostatic field simulation, calculation of swarm parameters for gas mixtures, and an avalanche breakdown model as described in [4]. Swarm parameters (coefficients for electron collision ionization and attachment, drift velocity, and diffusion coefficient as a function of reduced electric field in the range 5 Td to 500 Td) of a gas mixture consisting of nitrogen, carbon monoxide, carbon dioxide, hydrogen, methane, and water were evaluated using a code solving the Boltzmann equation in two term approximation being incorporated into a commercial software package [5]. A set of electron collision cross sections covering momentum transfer, vibrational excitation, electronic excitation, ionization, and attachment for all the compounds of the gas mixture was compiled from several sources such as [6] and [7].

Species	N_2	CO	CO_2	H_2	H_2O	CH_4
Volume fraction	0.426	0.185	0.111	0.185	0.074	0.019

Table 1: Composition of synthesis gas; the concentration of water in this gas mixture corresponds to 100 % relative humidity at 40 °C.

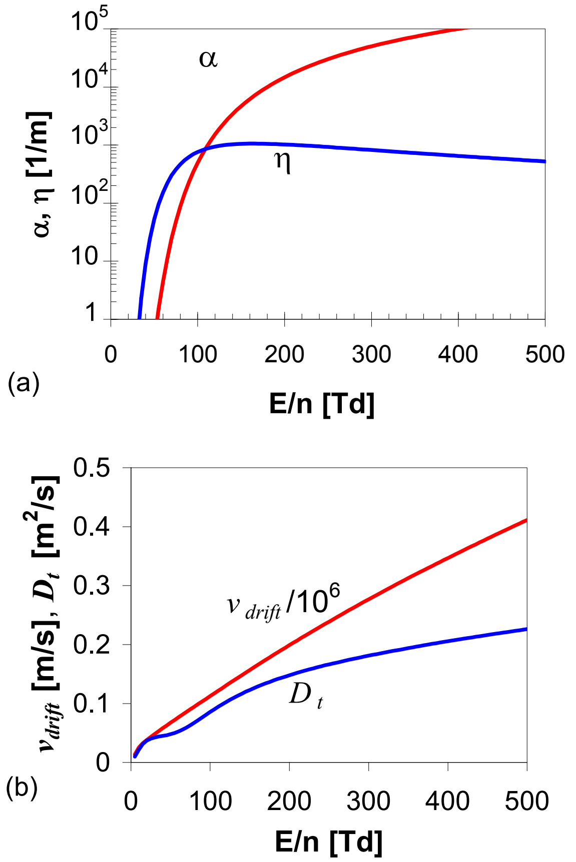


Figure 1 (a) Ionization- and attachment coefficients and (b) drift velocity and transverse diffusion coefficient of the synthesis gas mixture given in Table 1.

These swarm parameters were applied as input data for the evaluation of the avalanche breakdown voltages in a coaxial wire-cylinder geometry. The breakdown criterion was developed from Raether's one [8] by giving allowance for inhomogeneous electrical fields:

The electron number density in the avalanche head propagated for a distance s from the starting point s_0 is approximately given by

$$n_e(r,s) = \frac{v_{drift0}/v_{drift}}{(\pi \cdot \rho_{head}^2)^{3/2}} \cdot \exp\left\{ -\frac{r^2 + (s-s_0)^2}{\rho_{head}^2} + \int \alpha_{eff} \, \mathrm{d}s \right\}$$

where

v_{drift0}/v_{drift} is the ratio of electron drift velocity at the starting point of the avalanche to that at the actual position,

$\rho_{head}(s)$ is the diffusion controlled radius of the avalanche head, and

$\alpha_{eff} = \alpha - \eta$ is the effective ionization coefficient (difference of ionization and attachment coefficient),

which results in the electric space charge field at the electron avalanche head of

$$E_R(s) = \frac{e_0}{4\pi \cdot \varepsilon_0} \cdot \frac{v_{drift0}}{v_{drift}} \cdot \frac{\exp\left\{ \int \alpha_{eff} \, \mathrm{d}s \right\}}{4 \cdot \int D_e / v_{drift} \, \mathrm{d}s}.$$

Avalanche breakdown is assumed to occur if this field exceeds the external electric field. In the case of a coaxial wire-cylinder geometry the electric field as a function of voltage and radial distance from the center axis can simply be given analytically.

The results obtained for negative DC corona initiation by evaluation of avalanche breakdown voltages V_b and breakdown field strength at the wire surface E_0 as a function of wire radius r_w and tube radius r_t could be approximated by the following expressions:

$$E_0(A, B, r_w) = A \cdot \delta + B \cdot \sqrt{\frac{\delta}{r_w}}$$

and

$$V_b(r_w, r_t) = E_0(A, B, r_w) \cdot r_w \cdot ln\left(\frac{r_t}{r_w}\right)$$

with the gas specific parameters of syngas having 100 % RH at 40 °C

$$A_{SG40} = 3.39 \cdot 10^6 \ \mathrm{V/m}$$

and

$$B_{SG40} = 1.09 \cdot 10^5 \ \mathrm{V}/\sqrt{\mathrm{m}}$$

and of humid air (this deviates only slightly from the values cited in the literature)

$$A_{air} = 3.26 \cdot 10^6 \ \mathrm{V/m}$$

and

$$B_{air} = 1.18 \cdot 10^5 \ \mathrm{V}/\sqrt{\mathrm{m}} \,.$$

For the experimental conditions given in the introduction avalanche breakdown voltages of -13.1 kV and -14.6 kV (wet testing -14.5 kV) are obtained for synthesis gas and air, respectively. The simulated values for air differ for 2 kV from those obtained experimentally (about -12.6 kV). Good agreement between measured and simulated corona initiation voltages in air could be obtained when the parameters A_{air} and B_{air} were reduced for 14 % (wet ESP 11 %). This can be justified e.g. in order to take into account the surface roughness [11].

From synthesis gas testing corona initiation voltage around -10 kV were estimated. It was checked whether this deviation of roughly 20 % could e.g. be caused by tar or more general large carbon containing molecules being contained in the synthesis gas, which have ionization energies being several eV lower than those of the other components taken into account in the simulation of swarm parameters [12]. However, the tar concentrations of these synthesis gas mixtures were not large enough in order to increase the ionization coefficients simulated including such low ionization energy compounds.

Thus we have good reason for the assumption that the discrepancy between measured and simulated corona initiation voltage can be attributed to the particulate matter which also might reduce the breakdown voltage [13].

4 Current-Voltage Characteristics

In a second step the voltage current characteristics was evaluated using Townsend's approach for large current densities (see e.g. [1]). For this purpose the ion drift velocity in the gas mixture was estimated applying the approach of Mason and Hahn [9] and transport coefficients from [10]. For air the value cited in [1] was applied:

$$\mu_{air} \cdot n_{gas} = 2.14 \times 10^{21} \ / \mathrm{V} \cdot \mathrm{m} \cdot \mathrm{s} \,.$$

For the negative ions in humid syngas an average reduced mobility of

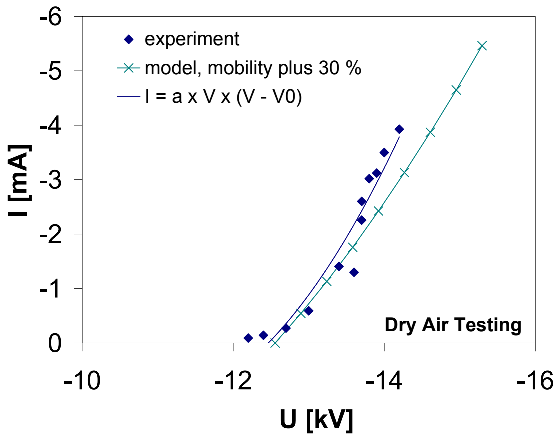
$$\mu_{syngas} \cdot n_{gas} = 4.8 \times 10^{21} \ / \mathrm{V} \cdot \mathrm{m} \cdot \mathrm{s}$$

was estimated. Since we do not have a complete ion chemistry model available for gas discharges in synthesis gas, it is not well known whether one of the negative ion species is predominating or not. Thus it is assumed that this average ion mobility estimation is not very reliable.

Together with the corona initiation voltages evaluated before this resulted in the current-voltage characteristics shown in Figure 2 for air and in Figure 3 for synthesis gas.

In order to get reasonable agreement between measured and simulated current-voltage characteristics, the ion mobility for air needs to be increased for about 30 % compared to the literature value. This effect could be caused by electrons contributing to the current in the drift region [14].

For synthesis gas the original value of the mobility was used. Since here information for full operation current and corona initiation is available, only, no conclusions about the mobility can be drawn.



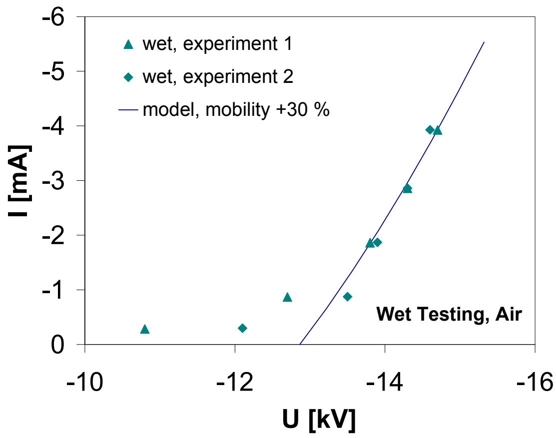


Figure 2 Simulated and experimental current-voltage characteristics of a negative wire-cylinder corona discharge in humid air (diameter of the wire 1 mm, inner tube diameter 52 mm); in the case of wet testing the water film was assumed to have a thickness of 1 mm. Corona initiation voltages were reduced for 14 % and 11 %, respectively.

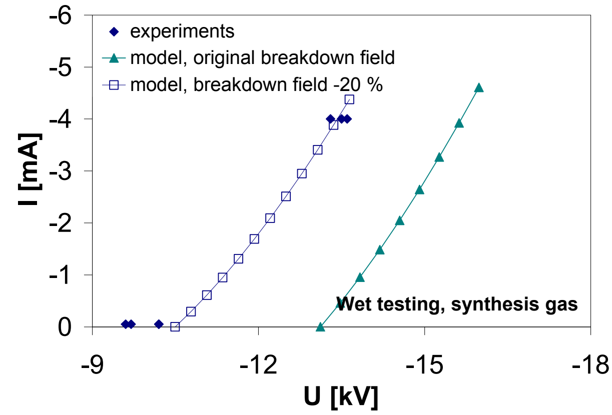


Figure 3 Simulated and experimental current-voltage characteristics of a negative wire-cylinder corona discharge in humid syngas.

5 Conclusions

Electrical properties of negative wire-cylinder corona discharges in humid synthesis gas have been simulated based on basic electron collision cross section data and ion mobilities.

For the evaluation of the corona discharge initiation voltage an avalanche breakdown criterion taking into account inhomogeneous electric fields was applied.

For the current-voltage characteristics Townsend's formula for large current densities was applied. Air was evaluated as a reference case.

Reasonable agreement between first tests of a wet ESP applied in a biomass gasification plant and these model results is observed. The results obtained for air give rise to the assumption that the corona initiation voltage is reduced for 10-15 % due to the surface roughness of the corona wire. Further it is assumed that in the case of synthesis gas containing substantial amounts of particulate matter an additional reduction of corona initiation voltage is caused by these particles.

The current-voltage characteristics measured in air corona indicate that electrons contribute to the current in the drift region.

6 Literature

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