Adsorption of Naphthalene on Activated Wood Charcoal Derived from Biomass Gasification

During gasification and/or pyrolysis of wooden biomass, charcoal is formed as a solid intermediate or product. In CO$_2$- and H$_2$O-rich atmospheres at high temperatures, a high specific surface area of several 100 m$^2$ per gram of charcoal may be reached. Common biomass gasifiers aim at a charcoal conversion of 100 %. Up to now, the option of a subsequent usage of the charcoal for adsorption of tar compounds has rarely been considered but is an interesting option to produce a clean syngas in a downstream adsorption unit. Experimental studies show an adsorption capacity of up to 0.4 g of tar per gram of charcoal using naphthalene as a model substance for tar. Respective adsorption isotherms, breakthrough curves in a fixed-bed adsorber, and a kinetic breakthrough model are presented.

Keywords: Activated wood charcoal, Adsorption, Biomass gasification, Breakthrough modeling, Naphthalene

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1 Introduction

Thermal gasification of biomass is an attractive technology for the sustainable conversion to syngas (fuel gas). Unfortunately, the raw gas frequently contains high amounts of mostly aromatic hydrocarbons, formed during the pyrolysis of the biogenic feedstock. These compounds have to be separated from the crude syngas before its use, e.g., in a chemical synthesis such as Fischer-Tropsch or methanol synthesis or as fuel gas in an electricity and/or cogeneration unit. These unwanted higher hydrocarbon species are commonly summarized as tars.

The adsorption experiments and modeling results presented in this work were part of a research and development (R&D) project for a new approach to biomass gasification. This process aims at the production of a clean syngas by using a concurrent moving-bed gasification reactor combined with a gas cleanup in a subsequent cooled adsorption section. The charcoal produced in the gasifier is thereby directly used as adsorbent for the tar species. Hence, the conversion of the charcoal primarily formed by pyrolysis by subsequent gasification with steam and carbon dioxide (to CO and H$_2$) has to be adjusted within the gasifier to ensure a yield of coke sufficient for adsorption. On the other hand, a certain degree of conversion of the pyrolysis coke with CO$_2$ and/or steam is needed to reach a high internal surface area of the adsorbent. The overall process and further information of this specific gasification process are given in a previous publication [1] and a respective patent [2].

Activated carbon is the most common material for adsorption applications that offers a large adsorption capacity for various compounds. The high capacity results from large internal surfaces and well adjustable pore structures [3]. As the reduction of fossil raw materials for the production of activated carbon is currently an environmental goal, a lot of work is done on the use of biogenic feedstock materials. Danish and Ahmad [4] give a present overview of the production and application of activated carbon from wooden raw materials, and they refer to several studies, where activated wood-derived charcoals are applied for water and gas cleaning.

Gaseous naphthalene, which is selected in this work as a model substance for the tar species, has also been examined as adsorbate on commercial and recycled activated carbon by Liu et al. [5] and Mastral et al. [6]. Nevertheless, these experiments were performed at higher temperatures and with carbon derived from lignite or biomasses such as coconut shells. Therefore, these results are not applicable to the conditions and the feedstock material (wood pellets) used here. Shen et al. [7] took different activated charcoal samples from biomass pyrolysis to adsorb phenol as a model substance for tar compounds. A maximum adsorption capacity of more than 0.7 g g$^{-1}$ could
be proved in this study but also without an investigation of the influence of temperature. In the work of Zhang et al. [8], the adsorption of benzene and naphthalene on two different activated carbons was examined for various temperatures. The results can also not be applied to this work since the relation of char conversion and adsorption capacity was not taken into account.

For an optimum design of the overall gasification process with integrated adsorption for gas cleanup, the adsorption capacity and kinetics were examined in this work as a function of the tar concentration and temperature of adsorption. In addition, the internal surface of the charcoal used for adsorption was also varied by pyrolysis of wood pellets and subsequent gasification (to a certain degree) with CO2. Finally, adsorption experiments in a fixed bed were conducted, and the resulting breakthrough curves were modeled.

2 Experimental Setup and Sample Preparation

For the determination of adsorption isotherms and breakthrough curves, a lab-scale adsorption unit with a fixed-bed reactor was employed (Fig. 1; conditions see Tab. 1). The temperature of the bed was controlled by an oil thermostat. The naphthalene concentration in the inlet gas stream was adjusted by a saturator with nitrogen as carrier gas. The temperature of the saturator was also controlled by an oil thermostat. An additional nitrogen flow was added just behind the saturator. The nitrogen flows were controlled by mass flow controllers. The concentration of naphthalene was in a range of only 75 mg m\(^{-3}\) (NTP) up to 8 g m\(^{-3}\) (NTP).

For the online detection of the naphthalene concentration at the outlet of the adsorber and the breakthrough of the tar (here naphthalene), respectively, air was added downstream of the adsorber for naphthalene combustion in a subsequent combustion tube. This enabled the (indirect) online detection of naphthalene (as CO\(_2\)) with a respective CO\(_2\) gas analyzer and prevented the deposition of naphthalene in the exhaust gas line. The combustion tube was heated electrically to 900 °C and filled with steel wool to maximize the surface and to catalyze the combustion step. All experiments were conducted with an overall volumetric flow rate of 200 L h\(^{-1}\) (NTP) and at atmospheric pressure. The determination of the equilibrium adsorption load was conducted by integrating the breakthrough curves and validated by a gravimetric analysis of the sample after the inlet concentration of naphthalene was reached at the outlet of the adsorber.

In the gasification process briefly described above, the charcoal is derived from the partial gasification of raw charcoal formed by wood pyrolysis. The properties of the charcoal, above all the internal surface area, strongly depend on the degree of conversion by gasification. For the determination of the influence of the conversion on the internal surface area of the residual carbon, different charcoal samples were produced. Standardized wood pellets from southern Germany in accordance with the local standard [9] were chosen; for characteristic data of this raw material see [1].

Raw charcoal samples were produced by heating up the wood pellets (1.5 kg) stepwise in a nitrogen flow in batch experiments until a temperature of 900 °C was reached (details in [10]). Thereafter, the char was partly gasified by CO\(_2\) (35 % in nitrogen) at 800 °C. The conversion of the charcoal (throughout this paper indicated with symbol \(X\)) was monitored by a gas analyzer for CO and CO\(_2\) and respective integration of the measured signals. Samples were taken at conversion degrees \(X\) of 0, 0.23, 0.33, and 0.59 with respect to the initial charcoal mass after pyrolysis. The conversion was limited to 60 %, as the mechanical stability of the charcoal then gets too low. Subsequently, the charcoals were used for adsorption experiments with the conditions mentioned in Tab. 1.

Table 1. Reactor dimensions, settings, and sample properties for the adsorption experiments.

| Parameter                                      | Value         |
|-----------------------------------------------|---------------|
| Inner reactor diameter [mm]                   | 25            |
| Length of adsorption bed (5 g charcoal) [mm]  | 30–70         |
| Porosity of fixed bed [-]                     | 0.4           |
| Adsorption temperature range [°C]             | 70–120        |
| Total pressure [bar]                          | 1 (atmospheric)|
| Concentration of naphthalene [g m\(^{-3}\) (NTP)] | 0.075–8       |
| Mass of charcoal [g]                          | 5 ± 0.1       |
| Conversion of raw charcoal (derived by wood pyrolysis) [-] | 0.0, 0.23, 0.33, 0.59 |
| Particle diameter [mm]                        | 4             |
| Particle length (average) [mm]                | 10            |
| Particle porosity [-]                         | 0.55, 0.66, 0.7, 0.82 |
| Particle density [kg m\(^{-3}\)]              | 824, 630, 550, 341 |
| Overall gas flow [L h\(^{-1}\)]              | 200           |

Figure 1. Experimental setup for the analysis of adsorption properties.
3 Model Equations

A transient one-dimensional adsorption model has been developed for the prediction of breakthrough curves. The respective mass balance considers the distribution of naphthalene in the gas phase and the adsorption on the charcoal.

\[
\frac{\partial C_n}{\partial t} = -\frac{u}{\varepsilon_b} \frac{\partial C_n}{\partial z} - \rho_b \frac{K_{LD}}{\varepsilon_b} (L_{eq} - L_{ads})
\]

(1)

\[
\frac{\partial L_{ads}}{\partial t} = k_{LD} (L_{eq} - L_{ads})
\]

(2)

\[\gamma_n = \frac{\rho_n}{\rho_b} \frac{\partial L_{eq}}{\partial \gamma_n}\]

(3)

For the approximation of the diffusion into the cylindrical char particles, the diameter of a sphere with an equivalent volume-to-surface ratio is used (here 5 mm). The apparent diffusion coefficient \(D_{app}\) in Eq. (3) is given by:

\[D_{app} = \frac{D_{eff}}{\varepsilon_p + K_p}\]

(4)

\[K_p = \rho_p \frac{\partial L_{eq}}{\partial \gamma_n}\]

(5)

\[D_{app} (see \ Eq. (4)) \ takes \ into \ account \ that \ the \ adsorption \ equilibrium \ has \ an \ influence \ on \ the \ adsorption \ rate \ and \ expresses \ that \ the \ rate \ – \ and \ thus, \ formally \ D_{app} - \ decreases \ with \ increasing \ strength \ of \ adsorption \ or \ more \ precisely \ with \ an \ increasing \ gradient \ of \ the \ loading \ with \ the \ concentration \ (here \ of \ naphthalene). \ For \ illustration, \ Fig. \ 2 \ displays \ the \ value \ of \ the \ particle \ porosity \ \varepsilon_p \ as \ well \ as \ of \ the \ factor \ K_p \ as \ a \ function \ of \ the \ concentration \ of \ naphthalene \ for \ the \ example \ of \ charcoal \ with \ a \ conversion \ of \ 60\% \ \ (\text{BET}) \ analysis \ was \ performed. \ The \ BET \ surface \ area \ of \ the \ raw \ charcoal \ from \ pyrolysis \ was \ determined \ to \ 61 \ \text{m}^2\text{g}^{-1}. \ A \ strong \ increase \ of \ the \ surface \ area \ to \ 453 \ \text{m}^2\text{g}^{-1} \ \ is \ reached \ for \ 20 \% \ of \ char \ conversion \ by \ gasification \ with \ \text{CO}_2. \ Thereafter, \ a \ slower \ and \ almost \ linear \ rise \ up \ to \ 884 \ \text{m}^2\text{g}^{-1} \ \ at \ a \ conversion \ of \ 0.6 \ \ was \ measured \ (Tab. 2). \]

\[D_{12} = \frac{1 \times 10^{-3} T^{1.75} \left( \frac{1}{M_1} + \frac{1}{M_2} \right)^{0.5}}{\rho_0 \left( \sum \Delta_1 \right)^{0.33} + \left( \sum \Delta_1 \right)^{0.33}}
\]

(6)

Knudsen diffusion is neglected since the main diffusion paths are meso-/macroporous.

4 Results and Discussion

4.1 Brunauer-Emmett-Teller Analysis

To characterize the charcoal samples, Brunauer-Emmett-Teller (BET) analysis was performed. The BET surface area of the raw charcoal from pyrolysis was determined to 61 \text{m}^2\text{g}^{-1}. A strong increase of the surface area to 453 \text{m}^2\text{g}^{-1} is reached for 20\% of char conversion by gasification with \text{CO}_2. Thereafter, a slower and almost linear rise up to 884 \text{m}^2\text{g}^{-1} at a conversion of 0.6 was measured (Tab. 2).

4.2 Adsorption Isotherms

To determine adsorption isotherms of naphthalene for the different charcoal samples, an adsorption temperature of 70 °C was chosen. This value was set as it is the target temperature for the gas at the outlet of the cooled adsorption section. Lower temperatures could fall below the dew point of the product gas and lead to condensation of water in the transfer line to the cogeneration unit. Experiments were performed with naphthalene concentrations in the range of 0.075–8 \text{g m}^{-3} for the charcoal samples with a degree of conversion by \text{CO}_2 between 0.2

1) List of symbols at the end of the paper.
and 0.6. The measured adsorption capacities, here denoted as the equilibrium load $L_{eq}$ of the particles with naphthalene (in g per g charcoal), could best be described by a Freundlich isotherm \[14\] with $g_{naph}$ as naphthalene concentration (in g m$^{-3}$) and $K_F$ as the coefficient of the Freundlich isotherm:

$$L_{eq} = K_F g_{naph}^{1/n}$$

All measured loads and the fitted Freundlich isotherms are presented in Fig. 3. The concentration range between 0 and 1 g m$^{-3}$ is shown separately, as such low tar concentrations are needed for a fuel gas utilized in a technical cogeneration unit.

With regard to the concept of biomass gasification with integrated tar adsorption \[1\], a required equilibrium load of 0.3 g tar per gram charcoal has been estimated for a charcoal conversion by gasification of 60% and a tar content in the raw gas of 15 g g$^{-1}$ (see \[1\]). As a value of 0.38 g g$^{-1}$ is measured for the load, at least for the model substance naphthalene (Fig. 3), this goal can now be considered as attained.

The overall height of the isotherms shows a strong dependency on the measured BET surface area as described in Sect. 4.1. As the cooling section of the designed gasification plant is not isothermal, the relation between the temperature and the adsorption properties must be considered. In theory, the capacity of an adsorbent is a function of the adsorption potential $A$ \[15\]:

$$A = R T \ln \left( \frac{c_{sat}}{c} \right)$$

$c_{sat}$ denotes the saturation concentration of the adsorbate. From this equation, a temperature-dependent equation with $\omega_0$ and $E$ as fitting parameters was derived by Astakhov and Dubinin \[16\], which is used here to determine the temperature- and concentration-dependent equilibrium load:

$$L_{eq}(A) = \omega_0 e^{-E/RT}$$

The pre-exponential parameter $\omega_0$ depends on the (measured) BET surface area and, thus, on the charcoal conversion $X$ (by CO$_2$). To obtain an adsorption capacity that includes the influence of the charcoal conversion $X$ (by CO$_2$), the equation given by Dutta et al. \[17\] was applied:

$$\omega_0 = \omega_0(X = 0) \left( 1 + 100 X e^{-0.5X} \right)$$

The value of $\omega_0 (X = 0)$ was determined based on an adsorption experiment at 70°C with a charcoal sample just prepared by pyrolysis of the wood pellets without subsequent treatment by CO$_2$ ($X = 0$) and a naphthalene concentration of 5 g m$^{-3}$.

To validate the temperature-dependent approach, two more experiments were performed at 100°C and 120°C, 5 g m$^{-3}$ naphthalene concentration, and a conversion of 0.59. Fig. 4

Table 2. BET results for charcoal samples produced by pyrolysis of wood pellets and subsequent gasification with CO$_2$ to a certain degree of conversion.

| Degree of conversion ($X$) with CO$_2$ | Parameter       | Value     |
|---------------------------------------|-----------------|-----------|
| 0                                     | $S_{BET}$ [m$^2$g$^{-1}$] | 61        |
|                                       | $S_{micropore}$ [m$^2$g$^{-1}$] | 47        |
|                                       | $d_{pore,av}$ [nm] | 2.4       |
| 0.23                                  | $S_{BET}$ [m$^2$g$^{-1}$] | 453       |
|                                       | $S_{micropore}$ [m$^2$g$^{-1}$] | 378       |
|                                       | $d_{pore,av}$ [nm] | 2.4       |
| 0.33                                  | $S_{BET}$ [m$^2$g$^{-1}$] | 667       |
|                                       | $S_{micropore}$ [m$^2$g$^{-1}$] | 524       |
|                                       | $d_{pore,av}$ [nm] | 2.4       |
| 0.59                                  | $S_{BET}$ [m$^2$g$^{-1}$] | 844       |
|                                       | $S_{micropore}$ [m$^2$g$^{-1}$] | 645       |
|                                       | $d_{pore,av}$ [nm] | 2.6       |

Figure 3. Freundlich isotherms for naphthalene on charcoal samples at different degrees of conversion by CO$_2$ during the preparation of the charcoal at 70°C adsorption temperature (5 g sample weight, 0.075–8 g m$^{-3}$ concentration of naphthalene, 200 L h$^{-1}$ N$_2$ (NTP) gas flow).
illustrates the model fits of the parameters $w_0$ and $E$. All experimental results and the universal model fits with Eq. (9) are indicated in Fig. 5. The fitting parameters for Eqs. (8) and (11) are given in Tab. 3.

### Table 3. Parameters for Freundlich isotherms and Eq. (11).

| Parameters | Value |
|------------|-------|
| $K_F$ ($[m^3g^{-1})^{1/2}$ | 0.19 |
| $n$ [-] | 22 |
| $K_F$ ($[m^3g^{-1})^{1/15}$ | 0.23 |
| $n$ [-] | 15 |
| $K_F$ ($[m^3g^{-1})^{1/13}$ | 0.32 |
| $n$ [-] | 13 |
| $w_0$ ($X = 0$) [-] | 0.02 |
| $b$ [-] | 1.65 |
| $\nu$ [-] | 0.81 |

#### 4.3 Breakthrough Curves

In all experiments for different concentrations, the breakthrough curves have been logged to gain information about the adsorption kinetics. For the implementation in the breakthrough model, the derivative of Eq. (9) with respect to the mass concentration has to be given for Eq. (5):

$$\frac{dE_{eq}}{d\gamma} = \frac{w_0 RT}{E} \left( \frac{M \cdot \gamma_n}{\gamma_c} \right)$$

(12)

For the unknown tortuosity $\tau$ (see Eq. (6)) the best model results were obtained assuming a linear decrease with increasing charcoal conversion $X$ for conversions between 0 and 0.6:

$$\tau = 17.44 - 19.4X$$

(13)

More and larger diffusion paths are formed with increasing conversion of the charcoal by CO$_2$ during the sample preparation. Hence, $\tau$ is 17.4 for $X = 0$ and only 6 for $X = 0.59$.

The experimental and model results for the adsorption breakthrough curves at charcoal conversions of $X = 0.23$, 0.33, and 0.59 are displayed in Fig. 6 for the three charcoal examples and initial naphthalene concentrations in a range of 0.5–5 g m$^{-3}$; the related values for the tortuosity of the charcoals are given in the captions.

The most accurate results are achieved for the samples with 59% char conversion. Predictions for the adsorption kinetics, as well as the integral of adsorbed mass are precise for all naphthalene concentrations. For the test series with a char conversion of 0.33, the kinetic behavior is predicted accurately.
Nevertheless, a failure in the integral of adsorbed mass occurs as a result of the tolerances of the $w_0$ parameter fit with Eq. (11). The predicted adsorption capacity therefore differs to a lower value in the model, as clearly visible in Fig. 6b. For samples with a char conversion of 23 %, the adsorption kinetics of the model are slightly faster than the experimental results at higher concentrations but increasingly accurate at low naphthalene contents. The physical root of the slower diffusion rates should be determined in further experiments on the structure of the material. The mass integrals of these samples meet the experimental results.

For the charcoal samples with $X = 0.23$ and 0.33, a breakthrough was measured almost immediately due to the very short adsorption bed length of only 35 mm (Fig. 6). Only for $X = 0.59$ and rather low concentrations of naphthalene (Fig. 6c), the breakthrough occurred after about 4 h. The mass of the samples was kept constant, but the bulk density of the bed decreased, and thus, the bed length increased significantly with rising char conversion. The aim of this study was not the determination of the breakthrough time, but the development of a reliable adsorption model. In case of a longer adsorption bed, the duration of the experiments would have prolonged excessively. Hence, this was not adjusted.

The model results for a much longer adsorption bed with 200 mm length as compared to the rather short bed length of the experiments with only 35 mm are illustrated in Fig. 7a for charcoals with a conversion degree $X$ (during the preparation by CO$_2$) of 23 %, 33 %, and 59 %. For the inlet concentration of naphthalene, a value of 0.5 g m$^{-3}$ was assumed. Now, the breakthrough would occur after about 20 h, which is
a value acceptable for technical applications. For this bed length, the charcoal with \( X = 0.59 \) (and the highest internal surface area, see Tab. 2) provides the steepest breakthrough curve but the lowest volumetric adsorption capacity. The latter fact is due to an increment of the particle porosity with increasing value of \( X \) (0.66 for \( X = 0.23 \) and 0.82 for \( X = 0.59 \), Tab. 1) and, therefore, a reduction of the charcoal mass for a given bed length (here 200 mm). The highest volumetric load with naphthalene is reached for a charcoal of about 33% conversion (Fig. 7b).

Note that in the concept of a concurrent gasification with integrated subsequent adsorption, as outlined in Sect. 1 and in [1, 2], the adsorption would be, strictly speaking, not conducted in a fixed-bed but in a moving-bed adsorber. In this case, the amount of charcoal leaving the gasification section has to be sufficiently high to avoid a breakthrough at any time, i.e., the velocity of the adsorption front has to be lower than the velocity of migration of the charcoal by gravity, but the discussion of these aspects is beyond the scope of this work.

5 Summary and Outlook

Experimental data of the adsorption of naphthalene on different charcoals in terms of adsorption isotherms and breakthrough curves are presented. The charcoals were produced from wood pellets by pyrolysis and subsequent partial gasification with CO\(_2\) until a certain conversion (\( X \)) of the raw charcoal (after pyrolysis) of up to 59% was reached. Naphthalene was used as a model substance for various tar species present in the product gas of biomass gasification.

A transient one-dimensional adsorption model was developed to predict the breakthrough curve for different values of conversion \( X \), initial naphthalene concentration, and adsorption temperature. This kinetic adsorption model considers the temperature- and concentration-dependent equilibrium load, here described by a Freundlich isotherm, as well as the influence of conversion \( X \) on the change of structural parameters such as the tortuosity and, thus, on the effective diffusion in the porous charcoal particles. The model agrees well with the experimental results and can now be applied for the design of the cooled adsorption section in a plant for biomass gasification with integrated tar adsorption.

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Symbols used

- \( A \) [J mol\(^{-1}\)] adsorption potential
- \( c \) [mol m\(^{-3}\)] concentration
- \( d \) [m] diameter
- \( D \) [m\(^2\)s\(^{-1}\)] diffusion coefficient
- \( E \) [J mol\(^{-1}\)] fitting parameter equilibrium load equation
- \( K_F \) [(m\(^3\)kg\(^{-1}\))^\(1/n\)] Freundlich isotherm coefficient
- \( k_{LDF} \) [s\(^{-1}\)] linear driving force factor
- \( K_P \) [-] inhibiting factor
- \( L \) [g g\(^{-1}\)] adsorption load
- \( M \) [kg mol\(^{-1}\)] molar mass
- \( n \) [-] Freundlich isotherm coefficient
- \( p \) [Pa] pressure
- \( R \) [J kg\(^{-1}\)mol\(^{-1}\)] gas constant
- \( t \) [s] time
- \( T \) [K] absolute temperature
- \( u \) [m s\(^{-1}\)] velocity
- \( X \) [-] conversion

Greek letters

- \( \beta \) [-] fitting parameter for inner surface equation
- \( \gamma \) [kg m\(^{-3}\)] mass concentration
- \( \Delta \) [-] diffusion volume
- \( \epsilon \) [-] porosity
### Variables
- \( \nu \) [-]: fitting parameter for inner surface equation
- \( \rho \) [kg m\(^{-3}\)]: density
- \( \tau \) [-]: tortuosity
- \( \omega_0 \) [-]: fitting parameter equilibrium load equation

### Sub- and superscripts
- 12: binary
- Ad: adsorption
- ads: adsorbed
- app: apparent
- av: average
- b: bulk
- BET: Brunauer-Emmett-Teller
- c: charcoal
- cur: current
- eff: effective
- eq: equilibrium
- LDF: linear driving force
- n: naphthalene
- p: particle
- s: superficial
- sat: saturation

### Abbreviations
- BET: Brunauer-Emmett-Teller
- NTP: normal temperature and pressure

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