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# MODELLING OF FLOW CONDITIONS IN DOWN DRAFT GASIFIERS USING THIN FILM MODELS

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## ABSTRACT

In order to examine how an inhomogeneous char bed affects the gas flow through the bed, a dynamic model have been developed to describe the flow distribution in a down draft gasifier. The gas flow distribution through the bed was determined using a thin film model approach. The temperatures in the bed were determined from a thermodynamic model of the gasification process.

Model calculations showed that a relatively small fraction of the gas was flowing through a part of the bed that was fuelled with smaller particles compared to a part of the bed that was fuelled with larger particles. The calculations also show that if the height of the two different parts of the bed were not evened out the bed would not be stable. However, if transport of particles from one part of the bed to the other occurred the bed would be stable.

*Keywords:* Gasification, modelling, pressure drop, stability.

## INTRODUCTION

During thermal gasification of biomass in down draft gasifiers it has been observed that at certain conditions the char is converted differently at different locations in the char bed. In extreme cases channels down through the bed can occur. This is unfortunate for number of reasons. It might lead to a reduction in the gas production from the gasifier. A channel through bed means that a part of the pyrolysis products passes directly through the bed and the beneficial effect of the char bed on the tar reduction will not be utilised [1]. Furthermore, an uneven char conversion could lead to an increased char loss from the gasifier.

In order to examine the importance of these phenomena a model that describes the flow in the char bed of a down draft fixed bed char gasifier has been developed.

The modelled gasifier is a two-stage gasifier with a thermal input of 100 kW based on the lower heating value. The gasifier is located at the Technical University of Denmark. The char gasification reactor and the externally heated pyrolysis unit are separated on this gasifier. Between the two units steam and preheated air are added. Practically, all the oxygen in supplied air reacts with a part of the pyrolysis products. This means that the temperature of the gas increases to around 1100 °C and therefore the main part of the tar from the pyrolysis process cracks. For further information about the two-stage gasification process the reader is referred to [2], [3].

## MODEL DESCRIPTION

The pressure drop across a bed of char particles depends on the size of the particles, the porosity

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of the bed and velocity of the gas flowing through the bed. These properties will be calculated applying a one-dimensional model of a down draft gasifier. For a description of the gasification process, a model by B. Gøbel has been employed. The model will only be described briefly here. For a more detailed description the reader is referred to [4], [5].

### Inhomogeneous char bed

When char is supplied to the gasifier, an uneven particle distribution and different particle packing across the bed can occur.

In this work it is examined how an inhomogeneous particle distribution will affect the gas flow through the bed, the char conversion etc. The system is modelled using a thin film model. A sketch of the principle of a thin film model is given in Figure 1. In the model the bed consists of two columns and the thin film approach means that cross flow in the char bed is neglected. Therefore, the flow through the two columns is distributed so the total pressure drop of the two columns is the same at any instant. For all calculations given here the cross section area is the same for the two columns.

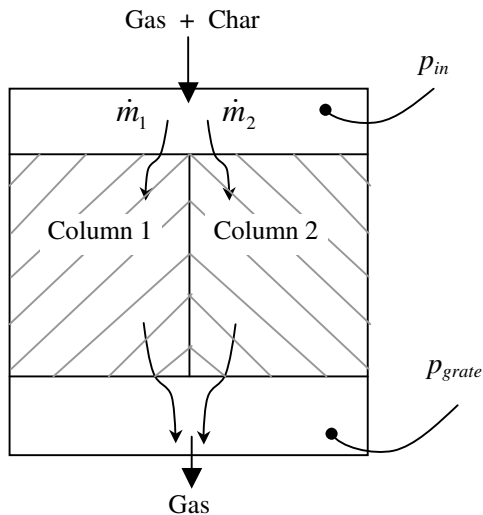


Figure 1: Sketch showing the principle of a thin film model applied on a char bed.

The model given here will be based on the following assumptions:

- A one-dimensional dynamic model can describe the gasification process.
- All particles are spheres and have the same diameter in any cross section through each of the two columns.
- The temperature is the same for both gas and char in any cross section through each of the two columns.
- The char conversion depends on temperature, the concentration of the species  $H_2$  and  $H_2O$  in the gas and the degree of conversion of the char.
- The gas consists of  $CO_2$ ,  $CO$ ,  $H_2$ ,  $H_2O$ ,  $N_2$  and  $CH_4$  only.
- $CH_4$  and  $N_2$  do not react in the bed.
- The gas composition follows the water-gas shift reaction
- The pressure drop through the porous bed can be determined from Erguns equation.
- All the gas flow around the particles -not through them.
- Heat loss to the walls of the reactor can be neglected.

On Figure 2 is shown a differential control volume for a cross section in the char bed. The figure also gives the applied sign convention.

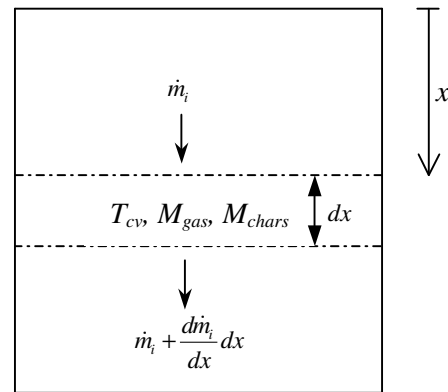


Figure 2: The control volume applied for the mathematical formulation of the thermodynamic system.

A mass balance for the control volume gives

$$\sum_i \frac{dM_i}{dt} + \sum_i \frac{dm_i}{dx} dx = 0$$

Where index  $i$  indicates which compound that is considered,  $M$  is the mass in the control volume,

$\dot{m}$  is the mass flow and  $dx$  is the thickness of the control volume.  $t$  is time.

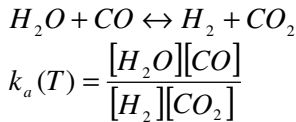
When heat loss from the bed to the walls of the reactor is neglected the first law of thermodynamics for the control volume can be written as

$$\sum_i \frac{dU_i}{dt} + \sum_i \frac{d(\dot{m}_i \cdot h_i)}{dx} dx = 0$$

$U$  is the internal energy and  $h$  is the mass specific enthalpy of the compound  $i$ .

### Gas-gas reactions

As mentioned earlier it is assumed that the gas consists of  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$  and  $\text{CH}_4$  only. Furthermore, it is assumed that  $\text{CH}_4$  and  $\text{N}_2$  do not react down through char bed. The compounds  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2$  and  $\text{H}_2\text{O}$  are assumed to be in thermal equilibrium and that the equilibrium concentrations can be determined from the water-gas shift reaction



where the equilibrium constant  $k_a$ , is given as

$$k_a(T) = 1.303 \cdot 10^{-6} T^2 + 7.17 \cdot 10^{-4} T - 1.3006$$

$$T \in [975\text{K}; 1525\text{K}]$$

### Char-gas reactions

The reactivity,  $r$ , of the char depends on the temperature, the concentration of  $\text{H}_2$  and  $\text{H}_2\text{O}$  and the degree of conversion,  $X$ , of the char itself. The reactivity is given as

$$r = -\frac{1}{M_{koks}} \frac{dM_{koks}}{dt}$$

$$= \frac{A \cdot \exp\left(-\frac{E}{R \cdot T}\right) \cdot n_3 \cdot T^m [\text{H}_2\text{O}]^{n_1}}{A \cdot \exp\left(-\frac{E}{R \cdot T}\right) + n_3 \cdot T^m [1 + n_2 [\text{H}_2]]} \cdot (k_1 + k_2 \cdot X + k_3 \cdot X^{k_4})$$

where  $[\text{H}_2\text{O}]$  and  $[\text{H}_2]$  are the mole fractions of respectively  $\text{H}_2\text{O}$  and  $\text{H}_2$ .  $R$  is the universal gas constant  $A$ ,  $E$ ,  $n_1$ ,  $n_2$ ,  $n_3$ ,  $k_1$ ,  $k_2$ ,  $k_3$  and  $k_4$  are empirically found parameters. The values of these parameters that are used here are valid for

standard gasifier fuel, SGF. The values of the parameters are determined experimentally from TGA measurements [5].

$$A = 1.50 \cdot 10^9, \quad E = 2.00 \cdot 10^5,$$

$$n_1 = 0.603, \quad n_2 = 7.053,$$

$$n_3 = 1.00 \cdot 10^{26}, \quad k_1 = 0.83,$$

$$k_2 = 0.294, \quad k_3 = 11.19$$

$$k_4 = 12.92, \quad m = 8.0.$$

### Pressure drop

The pressure through a porous media as i.e. char bed can be described by Erguns equation [6]

$$-\frac{dp}{dx} = \frac{150 \cdot \eta_{gas}}{d^2} \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot U + \frac{1.75 \cdot \rho_{gas}}{d} \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot U^2$$

Where  $\eta_{gas}$  is the dynamic viscosity,  $d$  is the particle diameter and  $\varepsilon$  is the porosity of the char bed.  $U$  is the gas velocity and  $\rho_{gas}$  is density of the gas.

### Particle models

The individual char particles will be porous due to drying and pyrolysis. Therefore the gasification processes will not only take place at the external particle surface but also to some extent in the core of the particles. To which extent the gasification takes place on the external surface or inside the particles depends on ratio between reaction rate of the gasification processes and the diffusion rate inside the particle.

If the reaction rate is high compared the diffusion the gasification will take place in the surface of the particle. In the opposite case time will be available for the gas to diffuse into the particle before the gasification will occur. The ratio between the reaction rate and the diffusion rate depends on parameters as temperature, gas composition, char properties etc. These phenomena will in this work be described with a simple model that says that

$$V = V_0 (1 - X)^n$$

where  $V$  is the particle volume,  $n$  is a parameter and  $X$  is the degree of conversion. When it is assumed that all particle are spherical the particle diameter,  $d$ , can be determined as

$$d = d_0 (1 - X)^{n/3}$$

and the density of the particle,  $\rho$ , is

$$\rho = \rho_0(1 - X)^{1-n}$$

The value of the parameter,  $n$ , can vary from 0 to 1.  $n=0$  corresponds to the extreme case where the very porous and the gasification reaction takes place evenly in the whole particle. This is called the porous particle model. The other extreme case,  $n=1$ , is when the gasification takes places at the surface of the particle only. This is called the shrinking core model. For  $n$  between 0 and 1 the particles are both shrinking and being increasingly more porous for increasing char conversion.

## RESULTS OF CALCULATIONS

### Particle models

In order to examine the importance of the parameter  $n$  in the particle model, calculations have been conducted. The mass flow of gas and char were fixed so the height of the char bed was 1 meter at stationary conditions. For these calculations both columns are fed with particles with a diameter of 15 mm. The uniform particle size means that the whole bed always will be homogeneous in any cross section.

For  $n > 0$  the density of the char decreases down through the bed. Therefore, the conversion takes place higher up in the gasifier for fuels which are described best with particle model with a low value of  $n$ , compared to a fuel with a higher value of  $n$ , as shown in Figure 3 that depicts the degree of conversion down through the char bed for different values of the parameter  $n$ . This also means the temperature decrease will occur higher in bed for fuels which are best described with low value of the parameter  $n$ , see Figure 4.

The pressure drop per produced amount of gas is shown in Figure 5 for different values of  $n$ . The figure shows that the pressure drop per amount of produced gas increase almost linearly with an increasing value of  $n$ . The calculations are, as mentioned earlier, performed for a constant bed height. If instead the mass flow of char and gas to the gasifier were kept constant the height of the bed would increase for decreasing values of  $n$ . In that case the pressure drop per produced amount of gas would decrease for increasing values of  $n$  [7].

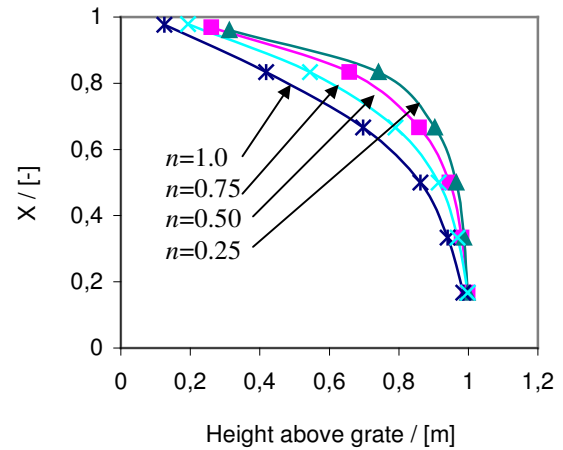


Figure 3: Degree of char conversion for different choice of particle model.

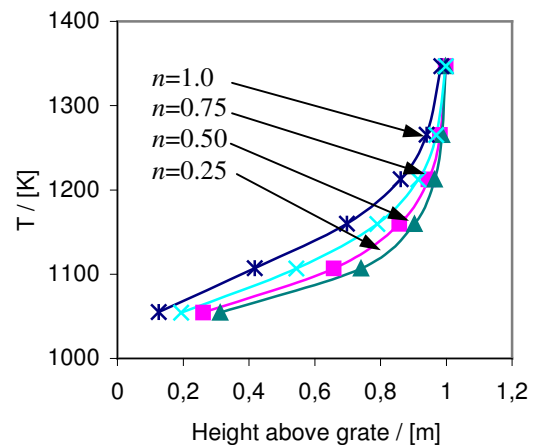


Figure 4: The temperature in the bed for different choice of particle model.

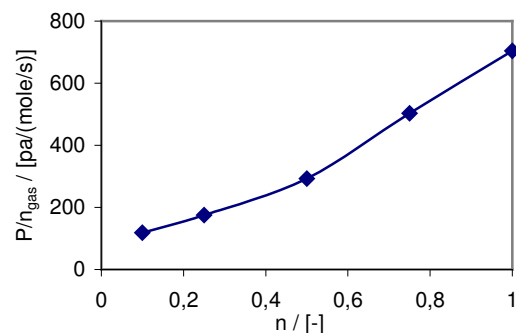


Figure 5: Pressure drop per produced amount of gas versus the parameter  $n$ .

### Inhomogeneous char bed

Calculations have been performed where same amount of char was lead to each of the two columns. One column was supplied with particles with a diameter of 15 mm and the other column was supplied with particles with a diameter of 10 mm. The flow resistance is largest for the column with the smaller particles and therefore a smaller fraction of the gas flows through this column compared to the other. A lower gas flow leads to a lower extent of gasification and therefore an increasing bed height for the column supplied with the smaller part. This is shown in Figure 6, showing the calculated height the two columns versus time. Apparently, the height of the column fed with the smaller particles almost linearly. In reality, this would not occur as the assumption of no cross flow is not valid when column height is too different and a part of the char would be transported from the higher to the lower column due to gravity. However, the results do show that the bed is unstable when the char is evenly distributed on the top of the bed.

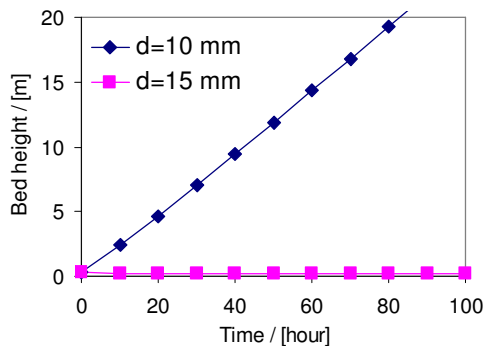


Figure 6: The calculated bed height for a constant char flow. The char is equally distributed to the two columns.

Instead of an even distribution of the char on the top of the bed a case with an uneven distribution has been modelled. This is done by assuming the char follows the gas or mathematically put

$$\frac{\dot{m}_{char,1}}{\dot{m}_{gas,1}} = \frac{\dot{m}_{char,2}}{\dot{m}_{gas,2}}$$

The results of these calculations are shown in Figure 7. Here it is seen that after some time both columns reach a certain stable height. The column fed with the smaller particles converges towards a

level that is higher than the column fed with the larger particles.

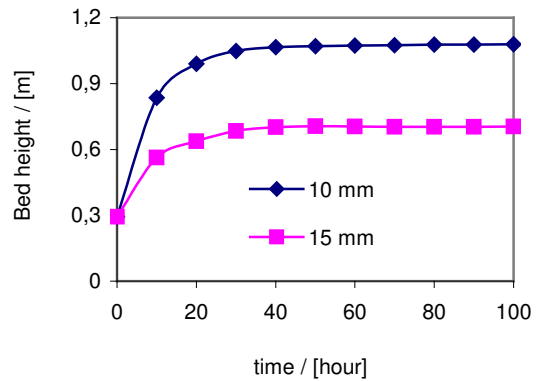


Figure 7: The calculated bed height for a constant char flow. The char is distributed as the gas.

A situation is modelled where the two columns are fed with 10 and 15 mm particles respectively and the mass flow of char is adjusted so the height of both columns is 1 meter at any instant. The amount of char that is supplied to the two columns is shown in Figure 8.

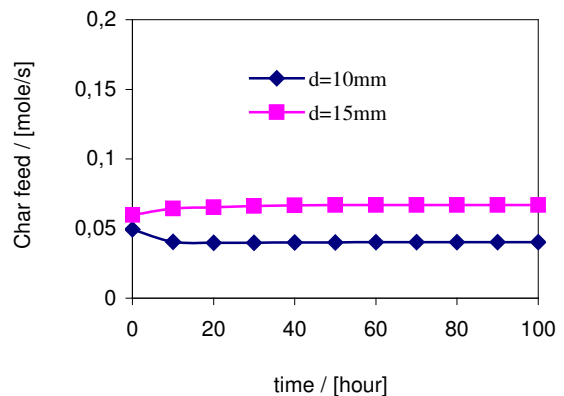


Figure 8: The char feed to the two columns.

As the height of the two columns becomes steady after some time it can be concluded that the system is stable. Even though the conversion rate is significantly different in the two columns the pressure distribution down through the columns is practically identical for the two columns, see Figure 9. This means that even if cross flow was possible it would hardly occur and that indicates that a thin film model approach is suitable for the applied purpose.

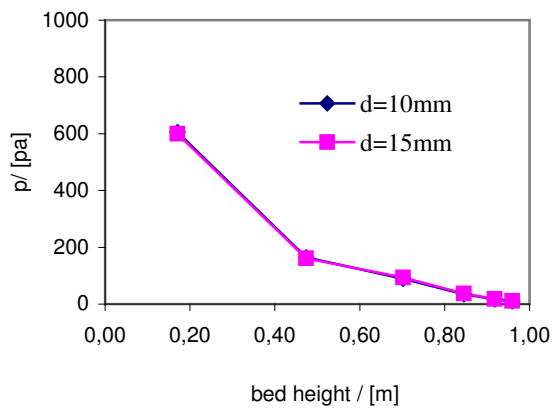


Figure 9: The pressure drop distribution down the bed.

## CONCLUSION

In order to examine how an inhomogeneous char bed affects the gas flow through the bed a dynamic model have been developed to describe the flow distribution in a down draft gasifiers. The gas flow distribution through the bed was determined using a thin film model approach.

The model showed that the pressure drop per produced amount of gas is lower for fuels that are described best using a porous particle model compared to fuels that are described best by a shrinking core model.

Calculation with an uneven particle size distribution to different part of the bed showed that:

- The char bed will not be stable if the char feeding is equally distributed across the bed.
- If the bed height is evened out in some way the system will be stable.
- The pressure drop profile in the columns of the thin film model is practically the same meaning that a thin film approach is suitable for the applied purpose.

## ACKNOWLEDGEMENT

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## NOMENCLATURE

$A$	Frequency factors
$d$	Particle diameter

$E$	Activation energy
$h$	specific enthalpy
$h_n$	Lower heating value
$k_1-k_4$	Empirical parameters
$k_a$	Equilibrium constant
$M$	Mass
$\dot{m}$	Mass flow
$m$	Empirical parameters
$n$	Parameter in particle model
$n$	Molar flow
$n_1-n_3$	Empirical parameters
$p$	Pressure
$R$	The universal gas constant
$r$	Reactivity
$t$	Time
$T$	Temperature
$U$	Internal energy
$U$	Gas velocity
$V$	Particle volume
$x$	Distance
$X$	Degree of char conversion

## Greek letters

$\eta$	Dynamic viscosity
$\varepsilon$	Porosity in the char bed
$\rho$	Density

## Indices

$0$	Initial state
$char$	Char
$cv$	Control volume
$gas$	Gas
$grate$	Condition below the grate of the bed
$i$	Compound
$in$	Inlet condition
$tot$	Total
$cv$	Control volume
$[\ ]$	Molar fraction of species

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