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DEMONSTRATION OF THE VORTEX PROCESS FOR BIOMASS GASIFIERS

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ABSTRACT: A new type of gasifier has been invented at the Technical University of Denmark, the Vortex gasifier. This gasifier is a staged gasifier in one unit. Hereby this type combines a simple construction with a very low tar content in the producer gas. By means of a special flow inside the gasifier the tar from the pyrolysis is brought to a hot area above the char bed, where the tar undergoes thermal cracking. Hereby the tar production from the vortex gasifier is reduced significantly and even without a complex shape of the reactor.

The process has been tested in different settings:

- The special flow causing the very low tar production has been verified in two different settings.
- Under conditions similar to those in the vortex gasifier the pyrolysis time has been investigated in order to find a relation between a minimum reactor diameter and the thermal input.
- A 100 kW down draft gasifier was operated as a vortex gasifier for a number of hours. Measurements indicated that the tar content in the producer gas from the vortex gasifier is very low.

The gasifier has been modelled in a stationary computer model to calculate the energy conversion efficiencies amongst other outputs.

Keywords: Biomass conversion, gasification, pyrolysis, tar removal, flow

1 INTRODUCTION

Thermal gasification of biomass still holds many challenges within research and development. One of the main problems is the tar production, which is an operational problem as well as an environmental problem. Around the world research and development is carried out on a range of gasification processes, in order to minimise the tar production and to develop efficient gas cleaning methods.

At the Technical University of Denmark a new simple type of gasification process with very low tar production has been invented and tested: The Vortex Process. In this paper the new process will be described for the first time, and there will be a presentation of the experiments carried out in order to verify the process.

2 THERMAL CONVERSION OF BIOMASS

Thermal conversion of biomass in a down draft gasifier can be split into two main processes: pyrolysis and gasification. Pyrolysis is endothermic conversion of organic material in a reducing atmosphere. The pyrolysis products are solid char and volatile components, like tar, pyrolysis gas and steam.

When a gasification agent is added to the char and the temperature is at least 750 °C the gasification process begins. The gasification agent can be air, oxygen, steam, carbon dioxide or a mixture of these. In the gasification process the char is converted into producer gas and ashes. The main components in the producer gas are carbon dioxide, carbon monoxide, methane, hydrogen and steam, but also some tar from the pyrolysis is found in the producer gas.

Tar from gasification processes is usually deposited in the condensate and therefore represents a potential environmental hazard. If the producer gas is used in an IC engine, the tar will cause problems here, for instance by blocking the valves. Therefore it is very important to reduce the production of tar from the process.

2.1 Staged gasifiers

In staged gasifiers the pyrolysis and gasification processes are separated. Between the two processes air is added, causing a partial combustion of the volatile pyrolysis products. Hereby the temperature will rise and a thermal cracking of the pyrolysis tars will occur. This induces a stable low tar production from staged gasifier. [1]

When the volatile pyrolysis products pass down through the char bed after the thermal cracking above the char bed, additional tar cracking will take place. [8]

3 THE VORTEX GASIFIER PROCESS

The vortex process is a down draft gasifier, where the pyrolysis and the char gasification take place in the same bed, and therefore only requires one unit. The pyrolysis takes place in the top of the bed and the gasification takes place further down in the bed separated from the pyrolysis by a special flow. Biomass is fed to the gasifier at the top and falls down on the top of the bed. To obtain reasonable efficiencies, it is advisable to pre-dry the biomass. The gasification agent is preheated air, which is supplied at the top of the gasification chamber. The producer gas is taken out at the bottom of the reactor. The heat in the producer gas can be utilised for preheating the air to the gasifier.

Since the tar content is expected to be very low, a bag filter is likely to be sufficient for cleaning the producer gas. After the gas cleaning system, the producer gas will be led to an engine to produce power and heat. The heat in the exhaust gas can be used for drying the biomass.

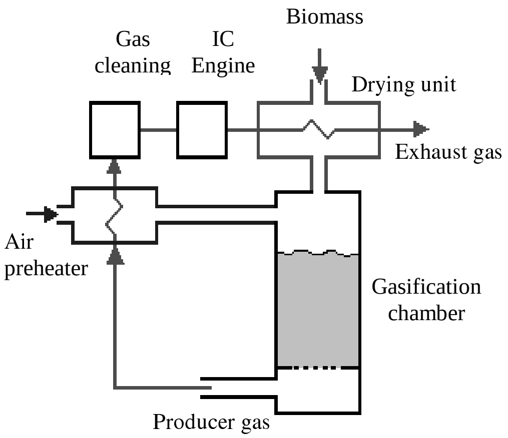

Figure 1: Outline of the vortex gasifier including a gas cleaning system and an engine

3.1 Flow in the vortex reactor

In the vortex process preheated air is supplied through three angled nozzles in such a way, that a horizontal rotating movement of the air is created.

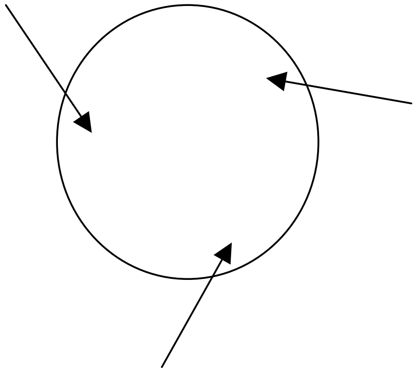

Figure 2: The three nozzles for air supply in the top of the reactor seen from above

When the rotating air reaches the boundary layer at the top of the char bed, the friction will reduce the radius of the rotational curve. Hereby a spiral towards the centre of the reactor is created, which is called secondary flow. The secondary flows towards the centre will be present both right on top of the bed and in the topmost part of the bed.

There will be a hot flow towards the centre in the top of the bed, where the convection in combination with the thermal gas radiation will cause the biomass to pyrolyse. Hereby volatile pyrolysis products are created. This will result in an upward flow of air and pyrolysis products in the centre of the gasification chamber.

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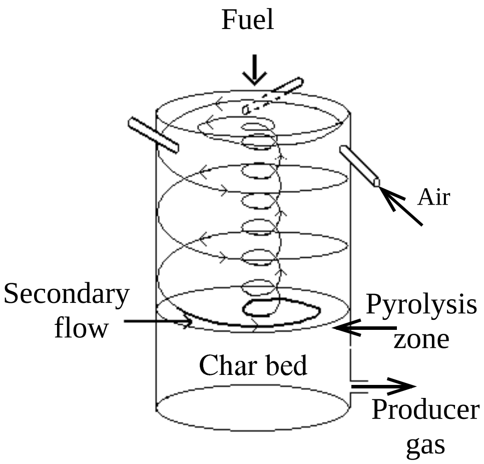

Figure 3: The flow in the top of the char bed and above the char bed in a vortex gasifier

The secondary flows will induce vertical circular movements in the top of and above the char bed.

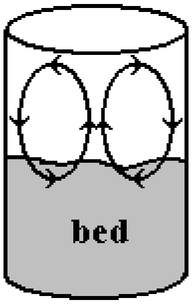

Figure 4: Vertical circular movements in and above the char bed

After the air and the volatile pyrolysis products have rotated a couple of times in the vertical circles in and above the char bed, they will pass down through the char bed. For further description of the vortex gasifier and the flow, see [2].

3.2 How can a low tar content in the producer gas be obtained?

Since the pyrolysis take place in the upper layers of the bed, the upward flow will bring the volatile pyrolysis products to the top of the gasification chamber above the char bed. Here the supply of air will cause a partial combustion of the volatile pyrolysis products. Hereby the temperature will rise to approximately 1100 °C causing a thermal cracking of the pyrolysis tars. Furthermore the gas will flow through the char bed where the residue tars will bee decomposed. Subsequently the content of tar in the producer gas from the vortex process will be low as for other staged gasifiers.

3.3 Compact pyrolysis zone

The high temperature above the bed causes high temperature gas radiation to the bed. Hereby the biomass will undergo pyrolysis in the top of the bed faster than for other down draft gasifiers. Therefore the pyrolysis zone is more compact in the vortex gasifier than in other down draft gasifiers. A rather compact pyrolysis zone is necessary to ensure that all the volatile pyrolysis products will be brought to the hot area above the bed by the vertical circular movements. This is necessary in order to crack a major part of the pyrolysis tar before it passes down

3.4 Advantages of the vortex process

One advantage of the vortex gasifier is that the gas producing part only consists of one unit. This gives a simple and relatively cheap construction.

Cracking of tars in the top of the reactor will reduce the tar content in the producer gas. Hereby it is easier and cheaper to reduce the tar content in the producer gas in the gas cleaning system to an acceptable level for an engine following the gasifier.

4 MODELLING THE VORTEX GASIFIER

A steady state computer model of the entire gasification system from biomass to heat and power was developed for the vortex gasifier [3 and 4]. The gasification model is a system model made up of a series of modules each covering one component. All major components from the drying unit to the engine and power generator including heat exchangers are modelled.

The energy outputs from the system are power and heat. High temperature heat is produced from cooling of the producer gas from the gasification chamber and of the exhaust gas from the engine. Low temperature heat for district heating is produced by the cooling of the engine and the power generator, condensation of steam from the drying of the biomass and end cooling of the producer gas and the exhaust gas.

A part of the high temperature heat can be used for internal heat exchanging to raise the temperature of the gasification agent and of the biomass in the drying unit. The higher the temperature of the incoming flows to the gasification chamber, the lower the need for airflow to the gasifier. With a lower airflow, the producer gas obtains a higher calorific value, and hereby the power conversion efficiency is increased. Therefore the internal heat exchanging system is very important for the efficiency of the plant.

The computer model is mainly based on mass and energy balances. The composition of the producer gas is determined by chemical equilibrium; the water-gas shift equation. For the engine model empirical data has been used. The model also takes into account the heat loss from each component in the system and from the hot pipes.

Since the test unit has only been operated as a vortex gasifier for a number of hours, data were not available to estimate the energy conversion efficiencies. Therefore the model has been applied for calculating the energy conversion efficiencies for a vortex gasifier of 3 $MW_{thermal}$.

Table1: Energy conversion efficiencies for the vortex process based on the computer model

	Vortex Process
Power conversion efficiency	32.6 %
Heat conversion efficiency	58.6 %
Energy conversion efficiency	91.2 %

The power conversion efficiency is calculated on the basis of lower calorific value. The efficiency of the engine at full load is 38% and the efficiency of the generator is 96.7%. The biomass used in the modelling has a moisture content of 50 % on wet basis, and the energy for drying is included in the calculations.

5 FLOW EXPERIMENTS

Using several different settings, selected features of the vortex process have been examined. The flow pattern, the pyrolysis time and the tar production are the main areas investigated.

The first objective was to examine whether or not the flows that are expected in the reactor will actually occur. The special secondary flow and the vertical circular movements are necessary to obtain tar cracking above the bed and hereby the low tar content in the producer gas. This was examined in cold flow experiments in a window reactor and in hot experiments in a 100 kW gasifier.

5.1 Hot experiments in a 100 kW gasifier

The hot flow experiments were carried out in a 100 $kW_{thermal}$ down draft gasifier at the Technical University of Denmark. The gasifier was operated as a vortex gasifier for some hours. The expected flow was confirmed by visual observation of a vortex and by temperature measurements. The visual observations were done through a small window in the top of the reactor, where a flaming vortex in the centre of the reactor above the bed was observed.

The temperature measurements showed that the temperature over the bed was above 1000 °C when the temperature inside the bed was between 700-850 °C. In a normal down draft gasifier the temperature above the bed would be lower than the temperature inside the bed. In the vortex gasifier it is the other way around since the partial oxidation of the volatile pyrolysis products will raise the temperature over the bed. In this way the partial oxidation will supply heat energy by means or radiation to the pyrolysis. In a normal down draft gasifier the energy for the pyrolysis is supplied from the flaming pyrolysis further down in the bed. The high temperature above the bed shows that there is a partial oxidation of the volatile pyrolysis products above the bed, which means that the flow must bring some volatile pyrolysis products to the top of the reactor.

5.2 Cold flow experiments in a window reactor

The flow was examined in cold flow experiments carried out in a partly transparent reactor containing wood chips. The airflow pattern was determined by sending smoke into the reactor and by using a streamer, whereby a visual image of the streamlines was created. In additional measurements of the dynamic pressure and the static pressure were made. These examinations were carried out for a number of different flow rates, different shapes of the reactor, different bed heights and different angling of the air nozzles.

Test unit: The test unit consists of a reactor with two windows, one at the front and one on the top. Air is supplied through three angled nozzles at the top of the reactor. Air or smoke can be added through a pipe at various places in the wood chip bed. It is chosen to correlate the volume of air added at the top of the reactor to the volume of air needed for a real gasifier of the same size. In the same way it is chosen to make the volume of air/smoke added through the pipe in the wood chip bed correspond to the volume of volatile pyrolysis products produced in a real gasifier of the same size. This results in much higher mass flows in these experiments compared to the real gasifier, since cold air and cold smoke is used. The air and smoke is let out in the bottom of the reactor.

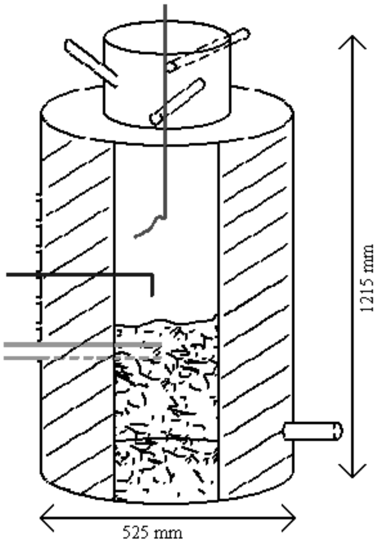

Figure 5: Window reactor for cold flow experiments.

Test with smoke: Smoke was sent in to the bed 5, 10, 15 and 20 cm under the bed surface, both in the centre and at the side of the bed. When smoke was injected 5, 10 or 15 cm under the bed surface a vortex of smoke was visible above the bed. This means that the volatile pyrolysis products both from the sides and from the centre of the topmost 15 cm of the bed are led to the area above the bed, where the partial oxidation and thermal cracking of the tar will take place.

Figure 6: Photo of the smoke vortex during cold experiments in the window reactor.

Test with streamer: The streamer was placed in different places in the reactor above the bed in order to see the direction of the flow. The flow was as expected, for instance in the centre, where the flow was upwards as can be seen on the photos below.

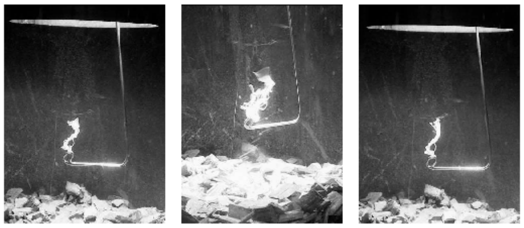

Figure 7: Photos of the streamer in the centre of the window reactor.

Measurements of the dynamic pressure: The size and direction of the dynamic pressure was measured with a pitot tube in the top of the bed and above the bed. The measurements showed that the flow was as expected.

Parameter variations: The angling of the nozzles was changed, to see how much the angling affected the efficiency of the vortex. It was observed that the vortex was created under a wide range of angles, but when the air was supplied almost tangential to the reactor, the vortex almost disappeared. The height of the bed surface was also changed, and the variations indicated that the vortex became stronger, when the distance between the air supply and the bed surface was reduced.

5.3 Discussion of flow experiments

Both the cold and the warm experiments clearly stated, that under various conditions the flow was as expected in the boundary layer in the top of the bed. For a 50 cm diameter reactor (100 kW gasifier) the secondary flow was detected in the topmost 15 cm of the bed. This implies that the volatile pyrolysis products are brought up to the hot zone above the bed where they will undergo thermal cracking. This is under the assumption that the pyrolysis in a 50 cm diameter reactor occur in the topmost 15 cm of the bed. This will be investigated by an analysis of the pyrolysis experiments.

It is assumed that the depth of the secondary flow will increase with increasing gasifier size, although the correlation between the size of the gasifier and the depth of the secondary flows has not been investigated in these experiments.

6 PYROLYSIS EXPERIMENTS

The possibility for the vortex process to be used in plants of different sizes has been investigated through pyrolysis experiments. The relation between a minimum diameter of the gasification chamber and the thermal input has been determined.

The minimum diameter of the gasification chamber does amongst others depend on the pyrolysis time for the wood chips, as the wood chips must be completely pyrolysed before they leave the zone with secondary flows. For a certain pyrolysis time the diameter must be so big that the wood is pyrolysed before it passes down under the zone with the secondary flows. If this is not the case, part of the volatile pyrolysis products will not be brought to the hot area at the top of the gasification chamber by the secondary flows and there will not be a tar reduction due to thermal cracking. Therefore the pyrolysis time is crucial for the relation between the reactor diameter and the nominal thermal input, if a low tar content is required. A demand for a big reactor diameter per thermal input could be critical in order to realise the process in larger scale.

In literature several different pyrolysis experiments has been reported, but no experiments based on conditions similar to those for the vortex gasifier was found. Therefore the pyrolysis time for wood chips has been examined by the application of two different methods in two different settings. Some experiments have been carried out in a 100 kW gasifier, and some have been carried out in a specially designed Macro Thermo Gravimetric Analyser (TGA).

6.1 Test in 100 kW gasifier

The pyrolysis time has been measured in the 100 $kW_{thermal}$ gasifier. Dry wood chips were dropped down through a small hole in the top of the gasification reactor. In the reactor they landed on the top of the char bed. The pyrolysis time was determined by measuring the time from the wood chip entered the hot gasification chamber until the colour of the chip had changed to that of the rest of the char in the bed. Experiments were carried out with wet and dry wood chips, and at different temperatures. The temperature in the bed varied between 800 °C and 900 °C and the temperature over the bed varied between 900 °C and 1050 °C. In some of the experiments the wood chips landed on the top of the char bed, and in other cases it fell down in small holes, being partly covered by char. The results varied, but indicated that the average time for the pyrolysis of dry wood chips in a vortex gasifier is approximately 1½ minute.

6.2 Test in Macro TGA

Test unit: For the other pyrolysis experiments a macro thermo gravimetric analysis unit (TGA) was designed and built. Here the mass of up to 30 g of wood chips was measured continuously during the pyrolysis. In order to have pyrolysis reactions and no gasification, it's important that there is no oxygen present in the reactor. Therefore nitrogen is added in several places.

The test unit is shown in Figure 8, and consists of a cylindrical pyrolysis reactor with a feeding tube which is angled downwards in order to prevent convection of hot gasses to the area where the wood chips are fed in. The wood chips are placed in the feeding tube, and pressed up to the pyrolysis reactor with a piston. Here the wood chips fall down on the scale, and the weight measurements start.

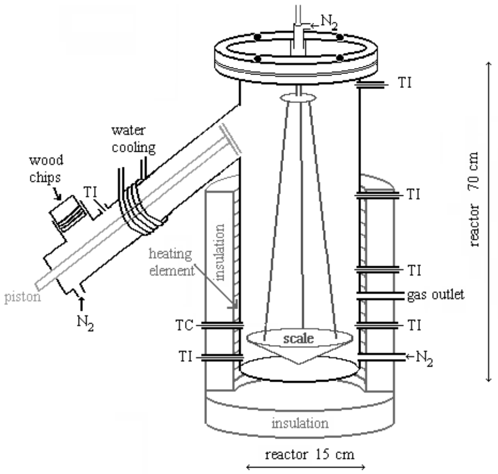

Figure 8: Macro TGA used for measuring pyrolysis time.

The pyrolysis time was measured as the time passing from the wood chips hit the scale until the mass had stabilised. The temperature in the TGA was varied between 400 °C and 1100 °C and wood chips of different sizes and moisture contents were used.

Experiments with varying temperatures: The experiments with varying temperatures showed that the pyrolysis time decreased with increasing temperature.

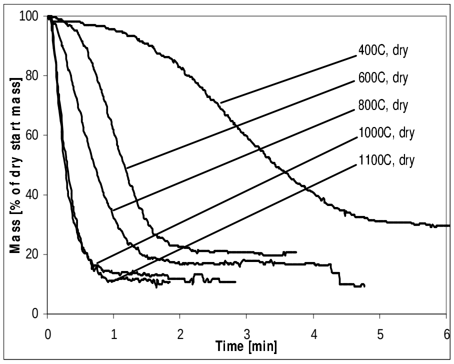

Figure 9: The mass as a percentage of the initial mass under the pyrolysis of dry wood chips at different temperatures.

The pyrolysis time is more temperature dependant for low pyrolysis temperatures, and it seems that for increasing temperatures the pyrolysis time reaches a minimum at 1 minute around 1000 °C.

The temperature in the top of a vortex gasifier will be approximately 800-1100 °C, and these experiments indicate, that the pyrolysis time for dry wood in this temperature range is about 1-2 minutes.

Experiments with varying moisture content: The experiments with varying moisture content showed that the pyrolysis time increased with increasing moisture content. Particular at low temperatures (400 and 600 °C, not shown on the graph) the pyrolysis time increased vastly with increasing moisture content.

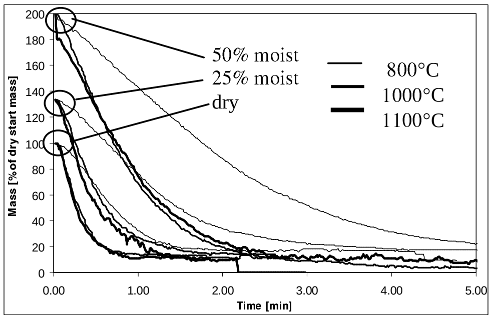

Figure 10: The mass as a percentage of the initial dry mass during the pyrolysis of wood chips with different moisture contents.

At the temperatures relevant for the vortex gasifier, the pyrolysis time for wet and dry biomass is found to be between ½ and 4 minutes.

These experiments clearly state that the pyrolysis time will be shorter if the biomass is dried before it is led to the gasification reactor. For dry biomass it is possible to reduce the size of the gasifier, and still all the volatile pyrolysis products will be brought to the hot area above the bed before they pass down through the bed. Therefore the biomass should preferably be dried before it is led to the gasifier in order to obtain a more compact gasifier and still have a low tar concentration in the producer gas. Pre drying also mean that at better power conversion efficiency can be reached.

Experiments with wood chips of different sizes: These experiments showed that the size of the wood chips did not affect the pyrolysis time significantly. As expected the pyrolysis time is slightly increased when using bigger wood chips. All the wood chips used in these experiments were dry.

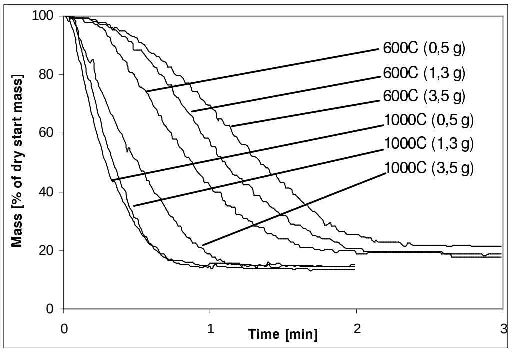

Figure 11: The mass as a percentage of the initial mass during the pyrolysis of dry wood chips of different sizes

The pyrolysis time for small and larger biomass is found to be approximately 1 minute for 1000 °C.

6.3 Discussion of pyrolysis experiments

Based on these experiments the pyrolysis time for wood chips was estimated to 1-3 minutes under conditions similar to those in a vortex gasifier. As described earlier, the secondary flow reaches a depth of 15 cm in a gasifier of 100 kW, and it is assumed that the depth will increase with increasing gasifier size. As a very conservative guess the depth of the secondary flow in a 2 MW gasifier is set to 15 cm.

On account of a pyrolysis time of 3 minutes and a depth of the secondary flow of 15 cm, it has been estimated that the diameter of the reactor in a vortex gasifier of 2 $MW_{thermal}$ should at least be of the order of 1 meter. Other factors can of course necessitate a larger diameter. In Figure 12 the minimum diameter for gasifiers of different sizes is calculated on basis of a pyrolysis time of 3 minutes and the assumption of the secondary flow reaching a depth of 15 cm in all gasifier sizes. It seems that the minimum diameters are realistic for all the gasifier sizes from 100 kW to 5 MW.

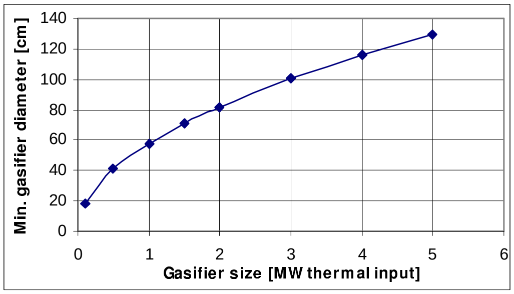

Figure 12: Minimum gasifier diameter for different gasifier sizes.

7 TAR MEASUREMENTS

The tar concentration in the producer gas from the vortex gasifier has been measured in order to examine whether there is a thermal cracking of tar above the bed resulting in a low tar content in the producer gas. The content of tar was determined through two different kinds of measurements on the 100 kW gasifier when operated as a vortex gasifier.

In order to determine the tar concentration in the producer gas, the SPA (Solid Phase Adsorption) method was used to take samples. The tar content was so low, that it was necessary to use a new method for analysing the samples. Therefore the analyses of the samples were rather uncertain. The SPA showed a tar concentration of 49 mg/Nm^3.

The tar in the producer gas was also determined by measuring the tar on the soot particles. These analyses showed a tar concentration in the producer gas between 42 and 44 mg/Nm^3.

Both kinds of measurements showed that the tar content was low like for staged gasifiers. [8]

The gasifier at the Technical University of Denmark was only operated as a vortex gasifier for some hours, which means that it might not have stabilised at the time of the measurements. This makes the result from the tar measurement even more uncertain, since the tar production might be different under more stable conditions.

8 CONCLUSION

A new type of gasifier has been invented at the Technical University of Denmark, the Vortex gasifier. This gasifier is a staged gasifier in one unit. This type combines a simple construction with a very low tar content in the producer gas.

Due to the secondary flow in the top of the fuel bed, the tar from the pyrolysis is brought to a hot area above the char bed, where the tar undergoes partial oxidation. Hereby the tar production from the vortex gasifier is reduced significantly and even without a complex shape of the reactor.

Pyrolysis experiments show that the pyrolysis time for wood chips was estimated to 1-3 minutes under conditions similar to those in a vortex gasifier.

Flow experiments show that the secondary flow reaches a depth of 15 cm in a gasifier of 100 kW, and it is assumed that the depth will increase with increasing gasifier size. This indicates that there is a basis for scaling up the vortex gasifier.

It has been experimentally demonstrated in different settings, that:

- The flow pattern above the bed behaves as expected.
- Pyrolysis can be completed within an acceptable time.
- The tar concentration in the producer gas is low.

On this basis it is concluded that the vortex process will work with a low tar production in a rather simple construction.

There have been applied for a patent on the vortex process.

9 ACKNOWLEDGEMENTS

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