Dual fluidised bed design for the fast pyrolysis of biomass

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ABSTRACT

A mechanism for the transport of solids between fluidised beds in dual fluidised bed systems for the fast pyrolysis of biomass process was selected. This mechanism makes use of an overflow standpipe to transport solids from the fluidised bed used for the combustion reactions to a second fluidised bed, which is used for the endothermic pyrolysis reactions. A screw conveyor is used to transport the solids back to the combustion fluidised bed.

Several experiments were performed on a cold model of the system in order to test the performance of the solid transfer mechanism in the dual fluidised bed design. It was found that the pressure drops over the combustion and pyrolysis fluidised beds were unaffected by changes in the speed of the screw conveyor and pyrolysis gas flow rate. The pressure drop over the pyrolysis bed was found to be mostly dependant on the flow of gas in the combustion bed due to its higher flow rate. As the combustion gas flow rate increased, the pressure drop over the combustion bed decreased and the pressure drop over the pyrolysis bed increased. This may be due to the flow of gas from the pyrolysis bed through the standpipe. A change in the amount of solids charged to the system had a negligible effect on the response of the pressure drop over the combustion and pyrolysis fluidised beds and the height of the solids in the pyrolysis bed to changes in the combustion and pyrolysis gas flow rate and the screw conveyor speed. However, an increase in the amount of solids charged did have a dampening effect on the rate of spills of solids into the overflow standpipe. It also stabilised the response of the rate of spills to changes in the combustion gas flow rate.

The solid transfer mechanism conformed to the requirements which were identified for the feasibility of the mechanism in the fast pyrolysis of biomass process. The proposed dual fluidised bed system is therefore a feasible system for the fast pyrolysis of biomass.

Keywords: standpipe, endothermic, cold model, thermochemical, solids transport, screw conveyor, L-valve

INTRODUCTION

Dual fluidised bed systems have been used extensively in the field of pyrolysis for the fast pyrolysis of biomass. Pyrolysis is an endothermic, thermochemical process in which the long polymers present in biomass are cracked in the absence of oxygen to form shorter polymers. The heat required for these endothermic reactions is usually provided by combustion reactions. In the dual fluidised bed system, the combustion reactions take place in a fluidised bed, which increases the temperature of solids. These hot solids are then fed to a second fluidised bed in order to provide the heat required for the endothermic pyrolysis reactions. In this way, the oxygen required for the combustion reactions does not interfere with the pyrolysis reactions.

Although many dual fluidised bed designs have been developed for the fast pyrolysis of biomass, little attention has been given to mechanisms for the transfer of solids between the two fluidised beds. The objectives of the current investigation was the selection of a solid transfer mechanism for dual fluidised bed systems, the experimental evaluation of its performance and the assessment of the solid transfer mechanism with respect to its applicability to the fast pyrolysis of biomass process. The following properties of the solids transfer mechanism were required in order for it to be suitable for the fast pyrolysis of biomass process:

• The mechanism should not allow for the transport of gas from the combustion fluidised bed to the pyrolysis fluidised bed.
• The mechanism should allow for the easy
control of the solids transfer rate, and therefore the rate of heat transfer, between the two beds.

- The construction of the solid transfer mechanism should not be too complicated or require a large amount of space.
- The solid transfer mechanism should not introduce large heat losses to the system.

A cold model of the proposed dual fluidised bed system was built in order to evaluate the performance of the solid transfer mechanism.

**LITERATURE STUDY**

**Fast Pyrolysis**

At elevated temperatures and in the absence of oxygen, the long polymers present in woody biomass decompose to form lower molecular mass compounds \(^1\). These compounds can be grouped into three divisions, namely tar, gas and char \(^2\). The tar and gas divisions both consist of gaseous compounds. However, the tar compounds are liquid at room temperature. The char division consists of solid residues of charcoal \(^3\). The pyrolysis of wood occurs in two stages as shown in Figure 1. In the first stage, wood is decomposed to form tar, gas and char compounds. In the second stage, the gaseous tar compounds decompose further to form char and gas compounds. The objective of fast pyrolysis is to minimize the residence time of this second stage in order to favour the formation of liquid products. The yield of tar compounds obtained from the pyrolysis of wood is very temperature dependant. It is therefore important to have control over the rate of heat addition to the pyrolysis fluidised bed.

**Common Solid Transport Mechanisms**

A literature study was performed in order to determine the common mechanisms that have been used to transfer solids in dual fluidised bed systems for either the pyrolysis or gasification of biomass. It was found that non-mechanical solid flow devices, such as L-valves, loop seals and standpipes, are preferred for both the transport from the combustion bed to the pyrolysis bed and from the pyrolysis bed to the combustion bed. The solids flow mechanisms selected by several authors for the transport of solids between the fluidised beds are shown in Table 1. From this table it can be seen that L-valves and loop seals are the most popular solids flow devices, which are used to control the rate of solid transfer between the fluidised beds.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Combustion bed to pyrolysis bed</th>
<th>Pyrolysis bed to combustion bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Cyclone →L-valve</td>
<td>Connection pipe →L-valve.</td>
</tr>
<tr>
<td>5</td>
<td>Cyclone →loop seal</td>
<td>Connection pipe</td>
</tr>
<tr>
<td>6</td>
<td>Connection pipe</td>
<td>Connection pipe</td>
</tr>
<tr>
<td>7</td>
<td>Cyclone →L-valve</td>
<td>Connection pipe</td>
</tr>
<tr>
<td>8</td>
<td>Cyclone →L-valve</td>
<td>Connection pipe</td>
</tr>
</tbody>
</table>

**DUAL FLUIDISED BED DESIGN**

The physical design of the dual fluidised bed system including the solid transfer mechanism that was chosen for the investigation is shown in Figure 2. Bed A in Figure 2 is the combustion fluidised bed, while Bed B is the pyrolysis fluidised bed. The solid that was chosen as the fluidization and heat transfer medium in this system is sand. Both the combustion and pyrolysis fluidised beds are planned to be operated in the bubbling fluidised bed regime. An overflow standpipe will be used to transport sand from the combustion fluidised bed to the pyrolysis fluidised bed. A screw conveyor, which is positioned at the bottom of both fluidised beds, will be used to transport sand back to the combustion fluidised bed. The entrance of the overflow standpipe will be positioned at the splash zone of the combustion fluidised bed. Sand should therefore spill continuously into the overflow standpipe.

![Figure 1: Two-stage biomass pyrolysis model](Image)

![Figure 2: Dual fluidised bed design](Image)
In order to simplify the construction of the fluidised beds, it was decided to use square beds rather than round beds. The combustion fluidised bed will be insulated with refractory, which separates the combustion bed from the pyrolysis bed. An advantage of this design is that the overflow standpipe may be built from the refractory separating the two fluidised beds. Therefore, the space required for this design is relatively small when compared to common fluidised bed designs.

EXPERIMENTAL

A 2D cold model of the dual fluidised bed system has been built at the Agricultural Research Service (ARS) in America, which is shown in Figure 3. The cold unit was built from transparent Perspex sheets in order to make it possible to view the height of the sand in the combustion and pyrolysis fluidised beds as well as the overflow standpipe.

In order to investigate the performance of the cold unit, several parameters were altered during the operation of the system and the resultant effects on the steady state values of the system were recorded. The following manipulated parameters were considered during the investigation:

- The speed of the screw conveyor.
- The flow rate of the gas fed to the pyrolysis fluidised bed.
- The flow rate of the air fed to the combustion fluidised bed.
- The amount of sand in the dual fluidised bed system.

Four different steady state values were considered during the experiments, which include the following:

- The pressure drop over the combustion bed
- The pressure drop over the pyrolysis bed
- The height of the sand in the pyrolysis bed
- The rate of spills or overflow of the sand into the standpipe per minute.

RESULTS AND DISCUSSION

Screw Conveyor Speed Results

The consequences of varying the screw conveyor speed on the circulating flow of the cold flow model have been found to give sufficiently accurate results and allowable assumptions from a statistical point of view. The effects of changing the speed of the screw conveyor on the pressure drop over the combustion and pyrolysis fluidised beds and the height of the medium in the pyrolysis fluidised bed is shown in Figure 4, while its effects on the rate of spills to the overflow standpipe is shown in Figure 5.

The experiment has given rise to the following conclusions:

■ As can be seen in Figure 4, the pressure drop over the combustion bed increased slightly as the speed of the screw conveyor increased. This is due to an increase in the amount of sand in the combustion bed as the speed of the screw conveyor increased. However, this increase in pressure drop is not significant.

■ The pressure drop over the pyrolysis bed remained approximately constant as the speed of the screw conveyor increased despite a larger quantity of sand that was removed from the bed. This is believed to be because of the standpipe which connects the pyrolysis bed to the combustion bed. The pressure drop over the pyrolysis bed is therefore dependent on the gas flow in the combustion bed rather than quantity of sand in the pyrolysis bed.

■ The height of the sand in the pyrolysis fluidised bed was directly influenced by the speed of the screw conveyor. An increase in the speed of the screw feeder would decrease the height of the sand in the pyrolysis fluidised bed. This is due to an increase in the amount of sand that was removed from the pyrolysis fluidised bed by the screw feeder.

■ The rate of spills into the overflow standpipe from the combustion fluidised bed was shown to be dependent on the speed of the screw conveyor. This rate peaked at a
Pyrolysis Gas Flow Rate Results

The objective of this experiment was to investigate the effects of varying the flow of gas to the pyrolysis bed on the circulating flow of the cold flow model. The results obtained for the pressure drop over the combustion and pyrolysis fluidised beds as well as the height of the sand in the pyrolysis fluidised bed is shown in Figure 6, while the rate of spills to the overflow standpipe is shown in Figure 7. The conclusions that were obtained from this experiment are the following:

- The pressure drop over the pyrolysis fluidised bed was not affected significantly by the flow rate of gas to it. This may be due to the gas flow through the overflow standpipe connecting the pyrolysis bed to the combustion bed. I.e. The pressure drop over the pyrolysis bed is dependent rather on the gas flow in the combustion bed because of its much greater flow rate.

- Similarly, the pressure drop over the combustion fluidised bed was not influenced significantly by changes in the flow rate of gas to the pyrolysis fluidised bed.

- It can be seen in Figure 6 that the height of the pyrolysis fluidised bed increased as the flow rate of gas to the bed increased. This is due to an increase in the void fraction of the bed. The lack of data points in Figure 6 is due to difficulties in accurately measuring the height of the bed at high gas flow rates.

Combustion Gas Flow Rate Results

The objective of this experiment was to determine the effects of varying the gas flow to the combustion fluidised bed on the steady state values in the cold model. The results obtained for the pressure drop over the combustion and pyrolysis fluidised beds as well as the height of the medium in the pyrolysis fluidised bed is shown in Figure 8, while the rate of spills to the overflow standpipe is shown in Figure 9. All measurements were taken after the minimum fluidisation velocity as the screw conveyor would seize until the bed was fluidised. The conclusions that were obtained from this experiment included the following:

- The pressure drop over the combustion fluidised bed decreased as the flow rate of gas to the bed increased. This may be due to an increase in the flow rate of gas...
The pressure drop across the pyrolysis fluidised bed increased as the flow rate of the gas to the combustion bed increased. However, this pressure drop began to decrease at a flow rate of 9.5 SCFM. This is because the standpipe was filled with sand at this point which reduced the flow of gas to the combustion fluidised bed.

The rate of spills into the overflow standpipe increased rapidly till a gas flow rate of approximately 9 SCFM. This is because the height of the combustion fluidised bed increased as the gas flow rate increased. However, above 9 SCFM, the rate of spills decreased till a gas flow rate of approximately 9.5 SCFM. This is because the increase in the gas flow rate from the pyrolysis fluidised bed through the standpipe prevented smaller clumps of sand from spilling into the stand pipe. Only larger clumps of sand were able to overcome the frictional drag caused by the gas flowing through the stand pipe and spill into the standpipe. Above a gas flow rate of 9.5 SCFM, the rate of spills began to increase again as the standpipe started to fill with sand, which reduced the gas flow through the standpipe allowing smaller clumps of sand to spill over into the standpipe.

**Amount of Sand Charged to the System**

The objective of this experiment was to determine the consequences of varying the amount of sand that was charged to the dual fluidised bed system. The screw conveyor speed, pyrolysis gas flow rate and combustion gas flow rate experiments were repeated with a larger volume of sand in the dual fluidised bed system in order to determine the dependence of these results on the amount of sand charged to the system. The results obtained for the pressure drop over the combustion and pyrolysis fluidised beds as well as the height of the medium in the pyrolysis fluidised bed versus the speed of the screw conveyor is shown in Figure 10, while the rate of spills to the overflow standpipe is shown in Figure 11. The conclusions that were obtained from this experiment are the following:

- The results obtained for the pressure drop over the combustion and pyrolysis bed, and the height of the sand in the pyrolysis bed is very similar to the results obtained in the first experiment. It was therefore concluded that a change in the amount of sand charged to the system does not significantly affect the outcomes of varying the screw conveyor speed with regards to these parameters.

- The rate of spills to the overflow standpipe went through a peak at approximately the same speed of the screw conveyor as in the first experiment. However, this peak was less substantial than in the first experiment. Therefore, it is believed that the increase in the amount of sand charged to the system has a dampening effect on rate of spills.
The results obtained for the pressure drop over the combustion and pyrolysis fluidised beds as well as the height of the sand in the pyrolysis fluidised bed versus the pyrolysis gas flow rate is shown in Figure 12, while the rate of spills to the overflow standpipe is shown in Figure 13. The conclusions that were obtained from this experiment are the following:

- The results that were obtained for the pressure drop over the combustion and pyrolysis bed, and the height of the sand in the pyrolysis bed is very similar to the results obtained in the first experiment. It was therefore concluded that a change in the amount of sand charged to the system does not significantly affect the outcomes of varying the gas flow rate to the pyrolysis fluidised bed with regards to these parameters.

- The rate of spills into the overflow standpipe showed a slight downward trend similar to the first experiment. However, the decrease in the rate of spills was much less than in the first experiment. This is because the weight of the additional sand in the pyrolysis reactor could overcome the upward drag force exerted on the particles by the pyrolysis gas flow.

The results obtained for the pressure drop over the combustion and pyrolysis fluidised beds as well as the height of the sand in the pyrolysis fluidised bed versus the combustion gas flow rate is shown in Figure 14, while the rate of spills to the overflow standpipe is shown in Figure 15. The conclusions that were obtained from this experiment are the following:

- The results that were obtained for the pressure drop over the combustion and pyrolysis bed, and the height of the sand in the pyrolysis bed is very similar to the results obtained in the first experiment. It was therefore concluded that a change in the amount of sand charged to the system does not significantly affect the outcomes of varying the gas flow rate to the combustion fluidised bed with regards to these parameters.

- The rate of spills on the other hand shows a very clear
linear correlation to the increase in the gas flow rate to the combustion bed. This is because the larger quantity of sand in the combustion bed easily overcame the frictional drag force exerted by the pyrolysis gas in the overflow standpipe. Therefore, we can conclude that an increase in the amount of sand charged to the reactor has stabilising effect on the rate of spills into the standpipe.

**Applicability to Fast Pyrolysis of Biomass Process**

Four requirements for the solid transfer mechanism were identified in order for the mechanism to be considered suitable for the fast pyrolysis of biomass process. The results obtained from the above experiments were used to determine whether the solid transfer mechanism selected in the current investigation conformed to these requirements. The results of this evaluation are shown in Table 2. It was found that the solid transfer mechanism selected conformed to all of the requirements identified for the fast pyrolysis of biomass process. It is therefore a suitable mechanism for this process.

![Figure 15: Rate of spills to overflow standpipe per minute](image)

**Table 2: Conformation of the solid transfer mechanism to the requirements for the fast pyrolysis process**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Conforms</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>The flow of gas from the combustion bed to the pyrolysis bed should be prevented.</td>
<td>Yes</td>
<td>It was possible to ensure that the flow of gas through the standpipe was from the pyrolysis bed to the combustion bed.</td>
</tr>
<tr>
<td>The solid transfer rate should be easy to control.</td>
<td>Yes</td>
<td>The flow rate of sand to the pyrolysis bed was dependant on the screw conveyor speed.</td>
</tr>
<tr>
<td>Construction of the mechanism should not be complicated or require large amounts of space.</td>
<td>Yes</td>
<td>The standpipe could be built from the refractory separating the combustion bed and the pyrolysis bed.</td>
</tr>
<tr>
<td>The solid transfer mechanism should not introduce large heat losses to the system.</td>
<td>Yes</td>
<td>The solid transfer mechanism does not require additional gas inlets to drive the movement of the solids, thereby reducing heat losses.</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

A feasible solid transport mechanism in a dual fluidised bed system for the fast pyrolysis of biomass was selected. The selected mechanism makes use of an overflow standpipe to transport solids from the combustion fluidised bed to the pyrolysis fluidised bed, and a screw conveyor to transport solids back to the combustion bed. Most dual fluidised bed designs for the pyrolysis or gasification of biomass make use of only non-mechanical solids flow devices to transport solids between the fluidised beds, such as L-valves and loop seals. The solid transfer mechanism selected is therefore a new approach to the transport of solid in dual fluidised bed systems for the fast pyrolysis of biomass.

Several experiments were performed on a cold model of the dual fluidised bed system selected in order to test the performance of the solid transfer mechanism. The experiments focused on the effects of changing certain parameters on the steady state values of the system. These parameters included the speed of the screw conveyor, the flow rate of the gas fed to the pyrolysis and combustion fluidised beds and the amount of solids charged to the system. The steady state values that were considered in these experiments were the height of the solids in the pyrolysis bed, the pressure drop over the pyrolysis and combustion beds and the rate of spills into the overflow standpipe per minute. The following important observations and conclusions were obtained from these experiments:

- The pressure drop over the combustion and pyrolysis fluidised beds were not influenced by the speed of the screw conveyor.

- The flow rate of gas to the pyrolysis fluidised bed had a negligible effect on the pressure drop over the pyrolysis fluidised bed. This is believed to be because of the gas flow through the overflow standpipe. The pressure drop over the pyrolysis bed is therefore mostly dependant on the flow of gas in the combustion fluidised bed due to its relatively higher flow rate.

- As the flow rate of gas to the combustion fluidised bed increased, the pressure drop over the combustion fluidised bed decreased and the pressure drop over the pyrolysis fluidised bed increased. This may be due to an increase in the flow rate of gas from the pyrolysis fluidised bed to the combustion fluidised bed through the standpipe.

- A change in the amount of solids charged to the system had a negligible effect on the response of the pressure drop over the combustion and pyrolysis fluidised beds and the height of the solids in the pyrolysis bed to
changes in the combustion and pyrolysis gas flow rate and the screw conveyor speed.

- The height of the solids in the pyrolysis fluidised bed increased with increases in the pyrolysis and combustion gas flow rates and decreased with increases in the screw conveyor speed.

- An increase in the amount of solids charged to the system had a dampening effect on the rate of spills into the overflow standpipe. It also stabilised the response of the rate of spills to changes in the combustion gas flow rate.

Four requirements of the solid transfer mechanism were identified which would aid its suitability for the fast pyrolysis of biomass process. It was found that the solid transfer mechanism selected in the current investigation conformed to these requirements. The proposed dual fluidised bed design is therefore a feasible design for the fast pyrolysis of biomass.

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REFERENCES


