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Primary Fragmentation of Wood in a Fluidized Bed Combustor - An Experimental Investigation

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ABSTRACT: This work presents the results of experiments conducted to quantify primary fragmentation of wood (*Casuarina Equisetifolia*) during the devolatilization in a bubbling fluidized bed combustor. Cylindrical wood particles having five different sizes ranging from 10 to 30 mm and aspect ratio (*l/d*=1) have been used for the study. Experiments were conducted in a lab scale bubbling fluidized bed combustor having silica sand as the inert bed material and air as the fluidizing medium. Studies have been carried out at three different bed temperatures (T_{bed}=750, 850 and 950 °C), two inert bed material sizes (mean size d_p=375 and 550 µm) and two fluidizing velocities ($u=5u_{mf}$ and $u=10u_{mf}$). Limited experiments were also conducted at a bed temperature of 850 °C to study the influence of the presence of wood bark. Primary fragmentation was found to be most severe for larger sizes and at higher bed temperatures. Also, fragmentation did not show any conclusive influence on the devolatilization time.

KEYWORDS: Wood; Devolatilization; Fluidized bed; Primary fragmentation.

1 INTRODUCTION

Devolatilization is an important stage of wood combustion, due to the amount of volatiles contained in it (~ 75% by mass) and the amount of heat contained in them (~ 80% by mass). Wood is known to shrink during devolatilization. It is also known to fragment under certain combustor conditions [1-3]. The fragmentation (breakage of initial wood particle into smaller char particles) during devolatilization is known as Primary Fragmentation. Both these phenomena (Shrinkage + Primary Fragmentation) greatly reduce the size of the wood particle. The reduced size could have significant influence on the heat conducted and oxygen diffusion into the particle and on the rate of the subsequent chemical reactions. Significant size reduction could result in elutriation of un-burnt fuel, thereby causing direct carbon loss. The size reduction could also play a dominant role in the sizing of the down-stream particulate collection equipment.

Therefore the size reduction could be beneficial as well as detrimental to the combustion process depending on its magnitude. The present work aims at finding the cause of primary fragmentation by quantifying it as a function of various operating conditions. For a wider range of applicability, experiments are conducted at different wood particle sizes, bed temperatures, inert bed material sizes and fluidization velocities.

2 EXPERIMENTAL

Experiments have been conducted in a lab scale fluidized bed combustor at three bed temperatures (T_{bed}=750, 850 and 950 °C), two inert bed material sizes (mean size d_p=375 and 550 µm) and two fluidizing velocities ($u=5u_{mf}$ and $u=10u_{mf}$). Details of the experimental facility, sample preparation, and experimental procedure have been discussed elsewhere by Sreekanth et al. [4, 5]. The Proximate and Ultimate analysis of Casuarina Equisetifolia is given in Table 1 below:

Table 1. Proximate and Ultimate analysis of Casuarina Equisetifolia

Quantity	Content (%)
Proximate Analysis	
Moisture	10.8
Volatiles	72.5
Fixed carbon	16.4
Ash	0.3
Ultimate Analysis	
Carbon	42.5
Hydrogen	6.1
Nitrogen	0.16
Oxygen	51.24

3 RESULTS AND DISCUSSION

3.1 PRIMARY FRAGMENTATION

On devolatilization, wood could undergo fracture or primary fragmentation. Fracture is the state when cracks form in the char particle but the particle itself is intact without breaking down. On undergoing primary fragmentation, the char particle fractures and further the fragments separate from the main body of the char. Hence primary fragmentation is defined as the breakage of the wood particle into smaller wood/char particles during devolatilization. It can be quantified by the Percentage of Fragmentation Events (SF), Number of Fragments (NF), Size Reduction Index (SRI) and Timing of Fragmentation (TOF).

3.1.1 PERCENTAGE OF FRAGMENTATION EVENTS (SF)

It is defined as the percentage of times a similar wood particle underwent fragmentation on repeating the experiment for a certain number of times. For example, on ten repetitions of a single particle experiment, if the particle fragments 6 times, the value of SF is 60%. It speaks about the consistency with which a wood particle would break. This takes care of the chance factor involved in a stochastic process like primary fragmentation. Figure 1 shows SF as it varies with size and bed temperature.

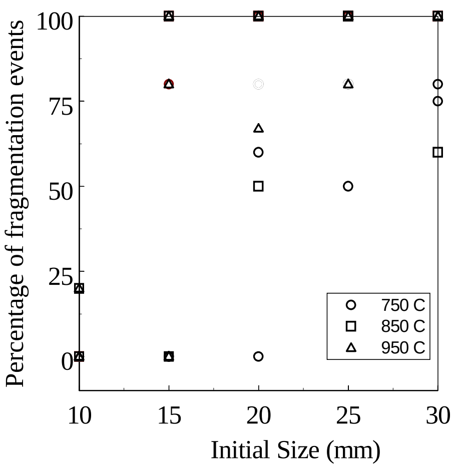

Fig.1. SF as a function of size and bed temperature

Two general observations can be made. First, as the initial wood particle size increases, the probability increases. Secondly, as the bed temperature increases, there is a rise in SF. Therefore high likelihood of fragmentation at larger sizes and bed temperatures can be observed.

Another important observation is related to the threshold size below which fragmentation does not occur. For a bed temperature of 750 °C, fragmentation does not occur for sizes equal to and below 15 mm. But for the other bed temperatures, fragmentation occurred even at the minimum size of 10 mm, though with a lesser frequency. For the 30 mm wood particle, the least chance is around 75% even at 700 ^{0}C.

3.1.2 NUMBER OF FRAGMENTS (NF)

It is defined as the ratio of the number of char pieces found at the end of devolatilization to the initial number of wood particles introduced. In the present study, only a single wood particle was introduced and hence NF is equal to the number of char fragments found at the end of devolatilization. The minimum value NF can take is unity, when no fragmentation occurred. Figure 2 shows the influence of size and bed temperature on NF.

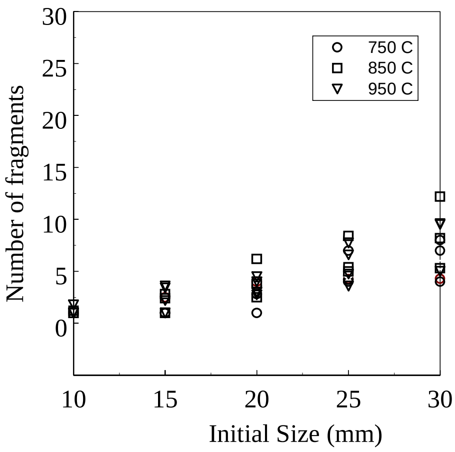

Fig.2. NF as a function of size and bed temperature

Again, there is an increase in NF with size and bed temperature, though the rise is not always consistent. This, too, indicates the stochastic nature of the process. In the figure, one would notice NF as fraction too. This is because of averaging the NF obtained in five repetitions. A 30 mm particle fragmented to 10-13 fragments at bed temperatures of 850 and 950 ^{0}C. A 20 mm particle fragmented to 5-7 particles at the same temperatures.

As pointed out in Section 3.1.1, fragmentation seldom occurred for 10 mm size wood. It would be interesting to compare the results of Ammendola et al. [6], where experiments on *Pinus radiata* wood of 10 mm size were found to fragment into 4.5 fragments, even at a bed temperature 800 ^{0}C. This fact cautions that each wood is different and has to be studies separately.

3.1.3 SIZE REDUCTION INDEX (SRI)

SRI, earlier known as Fragmentation Index (FI) according to Zhang et. al. [7] is a measure of the degree of size reduction a wood particle underwent. The name Size Reduction Index has been chosen for this study so as to also include shrunk [8, 9] but un-fragmented wood particles too. SRI is defined as:

$$\text{SRI}=\frac{NF}{\sum_{1}^{i}\frac{x_i d_i}{d_a}}$$

Therefore, the Size Reduction Index (SRI) includes both shrinkage as well as primary fragmentation in this study.

In the above equation, x_i is the mass fraction of the i^{th} fragment, d_i is the size of the i^{th} fragment and d_a is the initial size of the wood particle. In computing SRI, the value of d_i is taken as the mass equivalent sphere diameter of each fragment. This was necessary as the fragment shapes were usually irregular. Theoretically the minimum value SRI could take is unity. Even for an unfragmented wood particle, SRI at the end of devolatilization would be greater than unity because there was some size reduction due to shrinkage.

SRI is an indicator of the degree of size reduction achieved. Higher SRI indicates good size reduction. As an example, consider two similar wood particles each breaking into two fragments at the end of devolatilization. The first particle breaks into a larger and a smaller char particle while the second one breaks into two equal sized fragments. Since the second one could undergo larger size reduction, its SRI would be greater than the first wood particle.

Figure 3 shows the SRI as a function of size and bed temperature. SRI increases with size and bed temperature. SRI is observed to be higher for largest size and highest bed temperature. Its value ranges from little over 1 up to 25.

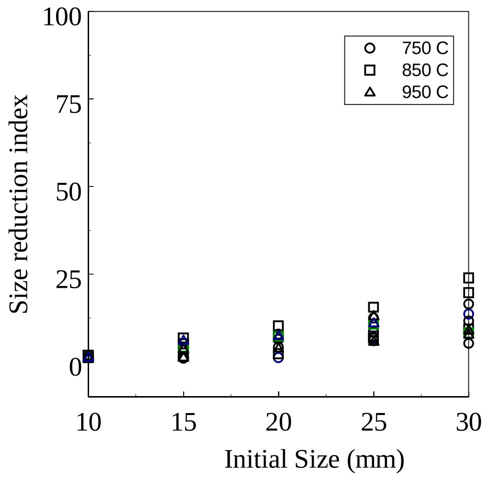

Fig.3. SRI as a function of size and bed temperature.

In general, smaller particles at lower bed temperatures, underwent only a fracture. This fracture was noted at two locations. First one at the centre, where an irregular radial crack was observed and second one near the periphery, where a clearly defined circular weak line was noticed. Also, the wood particle was found to have reduced to a minimal diameter (necking) at the mid point along the length. Under adverse conditions, i.e. at larger sizes and higher bed temperature, the char particle’s surface peeled and fell off, with a cracked but intact core remaining. On rare occasions during the entire experimental campaign, fragmentation across the length was noticed. Figure 4 shows the progress of the fragmentation process during devolatilization.

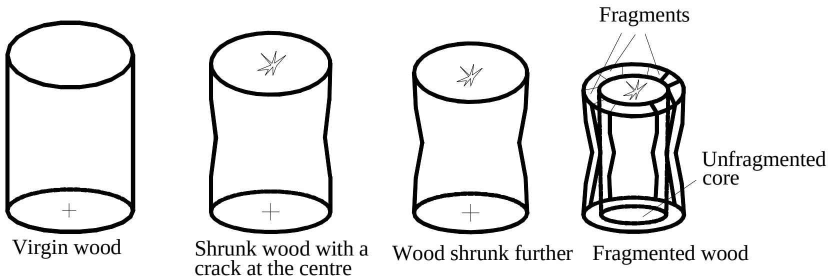

Fig.4. Sequence and mode of fragmentation of a wood

3.1.4 TIMING OF FRAGMENTATION (TOF)

Timing of fragmentation is an estimate of the time period during which fragmentation would occur. It also indicates the possible cause of fragmentation. If fragmentation occurred immediately after introduction, thermal shock could be the cause. If it occurred during the initial period of devolatilization, thermal stress could have been the cause. If it occurred at the middle of devolatilization time, volatiles pressure along with thermal stress could be the cause. If it occurred near to the end of devolatilization, the particle would have attained a uniform temperature and hence thermal stresses would have reduced. Therefore, weakening of the particle along with bed particle impact could be the cause. In addition, shrinkage could be a cause if fragmentation occurred during the end of devolatilization, because shrinkage increased rapidly during that period [10]. Figure 5 shows this phenomenon in wood cylinders at a bed temperature of 750 ^{0}C. For more detailed discussion on the time dependant shrinkage, the reader is referred to Sreekanth [10].

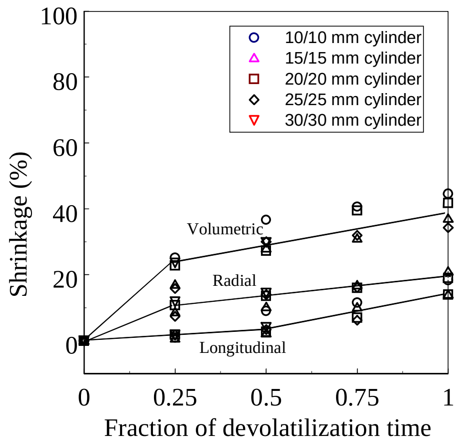

Fig.5. Progress of shrinkage during devolatilization. T_{bed}=750 °C.

Figure 6 shows the NF against the fraction of devolatilization time for different sizes at a bed temperature of 950 °C. Figure 7 shows the influence of bed temperature on the timing of fragmentation of a 30/30 mm particle.

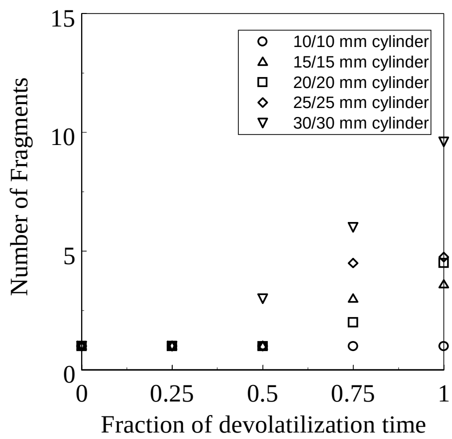

Fig.6. Timing of fragmentation at a bed temperature of 950 °C.

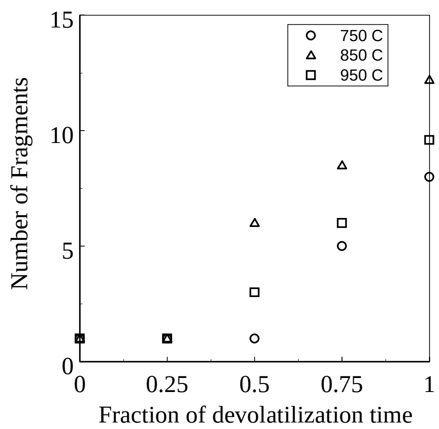

Fig.7. Timing of fragmentation of a 30/30 mm cylinder at different bed temperatures

It can be seen that the NF increases towards the end of devolatilization. Also there are few occasions where there is multiple fragmentation occurring, i.e. fragmentation taking place in the 3rd and 4th quarter too. Since fragmentation is observed near to end of devolatilization, it could be concluded that shrinkage stress along with particle weakening and bed particle impact could be the cause of fragmentation.

At this point, absence of fragmentation in smaller wood particles could be explained. As seen from earlier studies, radial shrinkage is higher in magnitude than longitudinal shrinkage [8, 9] and longitudinal shrinkage decreases with an increase in size while radial shrinkage increases only mildly [10]. Moreover as most of the heat is transferred in the radial direction, the thermal gradients and thereby thermal stresses are high in that direction. Hence radial stresses due to shrinkage and thermal gradients are higher in larger particles, causing fracture in them. This makes the particle weak and prone to failure. Such a particle on subjection to bed particle impact would undergo fragmentation. In smaller particles, since radial stresses are smaller, the particle only cracks at certain locations (centre and near the periphery). It does not become sufficiently weak so as to fragment under bed material impact. Also, in larger particles, char combustion begins at the surface while the interiors are still releasing volatiles. This could aid in further weakening of the surface.

3.2 Influence of Fluidizing Velocity And Bed Particle Size

Higher velocities and larger bed particle sizes have larger momentum and hence are capable of delivering larger impact to the char particle. Figures 8 and 9 show the influence of fluidizing velocity and bed particle size on the number of fragments. The results are against intuition. In a broader sense, the figures show that fragmentation is low at higher velocities and at larger bed particle sizes. This result is interesting and needs to be explained.

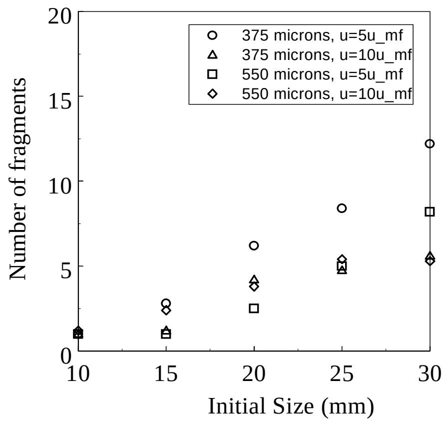

Figure 8: Influence of fluidizing velocity on the NF at a bed temperature of 850 °C.

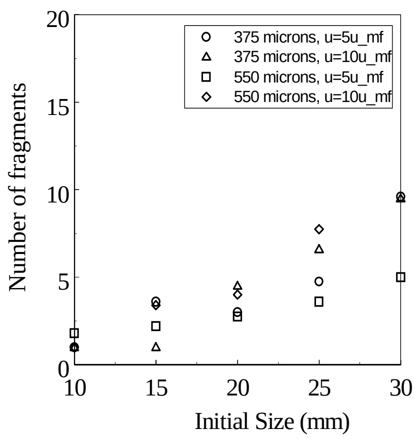

Fig. 9. Influence of fluidizing velocity on the NF at a bed temperature of 950 °C.

3.3 INFLUENCE OF FRAGMENTATION ON THE DEVOLATILIZATION TIME

Primary fragmentation exposes a large surface area of the particle thereby accelerating the reactions. However its influence on the process during which it occurs would be interesting to know. Figure 10 shows the devolatilization time for particles which fragment and also for particles which do not fragment at 850 °C. Figure 11 shows similar data at 950 °C. This data was obtained from experiments where only some of the particles underwent fragmentation. The solid symbols indicate un-fragmented particles while empty symbols depict fragmented ones.

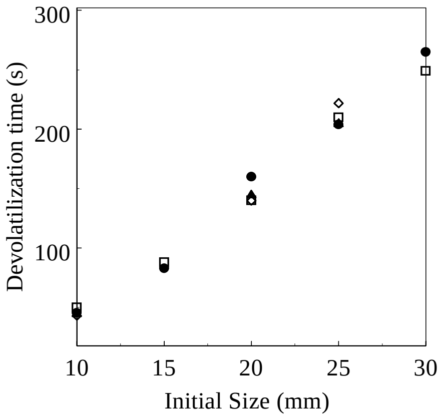

Fig.10. Influence of fragmentation on devolatilization time at 850 °C. Hollow symbols indicate fragmented particles and solid symbols indicate un-fragmented particles.

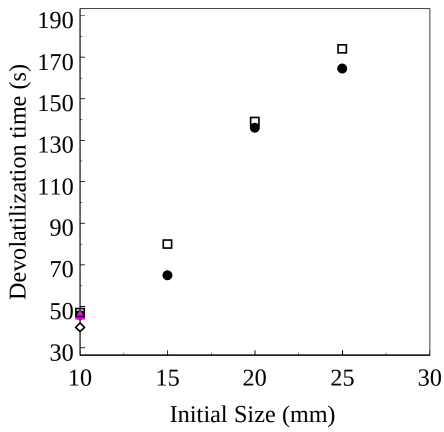

Fig. 11. Influence of fragmentation on devolatilization time at 950 °C. Hollow symbols indicate fragmented particles and solid symbols indicate un-fragmented particles.

There is no definite influence of fragmentation on devolatilization time. At times, the devolatilization time for fragmented particle was longer than the non-fragmented particle and at other times it was vice versa. This could be attributed to the experimental scatter. The absence of an influence could be due to the fact that fragmentation occurs at the end of devolatilization time, as indicated by the timing of fragmentation. Therefore most of the volatiles left the particle by the time of fragmentation.

3.4 INFLUENCE OF BARK

Wood constitutes of 5% bark, which is usually burned along with it. Bark could alter the heat transfer rate into the particle, by forming an additional resistance to heat conduction and oxygen diffusion. Also, it could hold the char so that it does not undergo fragmentation. In order to study the influence of bark, wood of 25 mm diameter (which was the only size with bark, among the sizes studied) and 25 mm height was used. Figure 12 shows the devolatilization times of 25/25 mm wood samples with and without bark, subjected to a bed temperature of 850 °C.

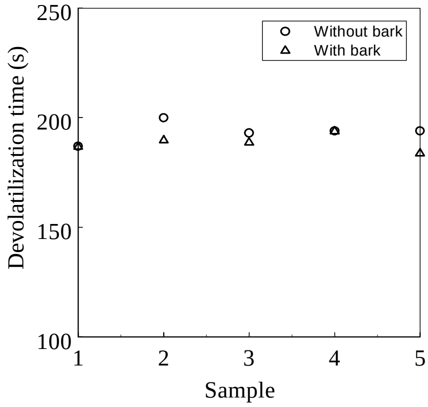

Fig. 12. Influence of bark on the devolatilization time of a 25 mm wood particle at a bed temperature of 850 °C

It can be seen that the difference is negligible. Also the number of fragments with bark and without bark ranged from 4-12 and 5-10 respectively while the average NF was 8.4 for both cases. Similarly the size reduction index was found to be 15.5 for both cases. Though this appears to be too much coincidence, from the limited experiments conducted, it could be concluded that presence of bark has no influence on the devolatilization time, NF and SRI.

4 CONCLUSIONS

1. Primary fragmentation takes place mostly for particles above 10 mm size and at higher bed temperatures.
2. The Number of Fragments varies from 1 to 13 in the range studied.
3. The Size Reduction Index varied from over 1 to 25 in the range studied.
4. No clear influence of fluidizing velocity and bed particle size was observed.
5. Primary fragmentation occurs in the 3rd and 4th quarter of the devolatilization time.
6. Devolatilization time is independent of the occurrence of fragmentation for the species of wood studied.
7. Presence of bark does not influence the devolatilization time and primary fragmentation characteristics.

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