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Smoldering Combustion of Biomass Particles

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Abstract: An experimental investigation of smoldering combustion of teak wood and cow dung particles has been carried out. Fuel characterization analysis in terms of the calorific value and thermo-gravimetric data has been performed with both fuels. Sieved particles of biomass are stacked into a thin paper tube, in which, the smoldering combustion is studied by igniting one end of the tube and by recording the rate of regression of the tube length. The paper tube has been kept in 3 orientations with respect to normal gravity (vertical) direction and smoldering rates for each orientation have been measured using both fuels. The results show that, based on the fuel characteristics, orientation plays an important role in deciding the smoldering rate.

Key words: Biomass, teak wood, cow dung, smoldering, regression rate

INTRODUCTION

Smoldering is a slow, low-temperature, flameless combustion, sustained by the heat evolved when oxygen diffuses into the surface of a solid fuel. Smoldering constitutes serious fire hazard due to a couple of reasons. First, conversion of a fuel to flammable compounds in substantial amounts can occur, even though the process is slow. Second, smoldering can result in flaming, initiated by heat sources, which cannot directly produce a sustained flame. Smoldering is different than a non-flaming gasification process that occurs when a condensed phase organic material is subjected to an external heat flux. Any organic material, when subjected to sufficient heat flux, will degrade, gasify and gives-off smoke. This is not an oxidation process; however, smoldering is an oxidation process. A burning cigarette is a familiar example of typical smoldering combustion. The finely divided fuel particles provide a large surface area per unit mass of fuel, over which, heat as well as oxygen diffusion can occur. The porosity involved in the aggregate of fuel particles permits oxygen transport into the reaction zone by diffusion and convection. On the other hand, the same particle aggregates typically can act as effective thermal insulators, which slows down the heat losses and facilitate sustained combustion despite low heat release rates of smoldering. Furthermore, these physical factors such as heat and oxygen diffusion that favor smoldering is complemented by chemical factors such as chemical kinetics. The initiation of smoldering process is predominantly due to chemical kinetics governing the oxidation of the solid fuel. Subsequent propagation of the smolder-front is controlled by the rate at which oxygen is transport into the reaction zone. The reaction continues consuming oxygen reaching the reaction zone. When oxygen is consumed, oxygen level reduces locally, which limits the reaction rate. Therefore, subsequent evolution of smoldering away from the initiation region is heavily influenced by oxygen supply conditions. In devices such as fluidized bed combustors, fine particles of solid fuel (coal and biomass) are employed. The fuel handling systems would have a collection of layers consisting of these particles. Onset of ignition in these would cause smoldering type of reaction to initiate, which can grow to a fire scenario later, depending on the oxygen supply conditions.

Studies on smoldering process have been extensively reviewed by Ohlemiller (1995). Kashiwagi and Ohlemiller (1982), Di Blasi (1993) and Kashiwagi (1994) have examined the effect of gas-phase oxygen on the gasification of condensed phase employing polymers such as polymethylmethacrylate (PMMA) and polyethylene (PE). Thermal effects on the gasification of non-charring polymers such as PMMA in an oxidative environment have been studied by Esfahani (2002). For given thermal radiation heat flux, calculations were made to predict the temperature field within the polymer. Schult *et al.* (1995, 1996) studied the physics of propagation and extinction of forward and opposed smolder waves in forced convective flow.

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The characteristics of log smoldering were described by Rabelo *et al*. (2004). They reported that lower smoldering speeds were observed during night time and higher speeds at daytime for the same log. Also, moisture content in the log affected the smoldering rates. Mukunda *et al*. (2007) carried out experimental and theoretical studies on the smoldering rates of incense sticks as a function of ambient oxygen fraction in air, the flow velocity and size. A correlation for the non-dimensional smoldering rate with radiant flux from the surface and heat generation rate at the surface was proposed. Smoldering combustion in cigarette smoking as well as the generation of combustion products has been studied by Senneca *et al*. (2008). In this study, smoldering combustion of particles of teak wood and cow dung (biomass) is studied for characterizing the solid fuel in terms of how ignition initially occurs and propagates within the solid. This study would also lead to understanding of the combustion in a charring solid fuel (biomass) in a better way. First, fuel characterization studies such as estimation of calorific value using a bomb calorimeter and thermo-gravimetric analysis have been carried out with fuel samples. Subsequently, smoldering combustion in these particles has been studied by stacking them within a thin circular tube made out of cigarette paper. The tube is kept at horizontal, vertical and upside-down orientations and the rate of smolder front propagation has been recorded in terms of regression rate of the length.

MATERIALS AND METHOD

Fuel is dried, ground to powder form and sieved to have a given maximum particle size. In this study, teak wood powder having a maximum particle size of 0.5 mm and the cow dung powder having a maximum particle size of 0.7 mm, have been employed. To arrive at the typical density of packing, first the powders have been packed in to a rigid metal tube closed at its bottom end, by applying a little pressure at the open end at the top. After making it to settle, the excess powder on the top has been removed and the powder effectively packed inside the rigid tube has been weighed. Typical densities of teak wood and cow dung powders have been estimated as 354 kg m^{-3} and 346 kg m^{-3}, respectively. For conducting experiments, dry particles of teak wood and cow dung are stacked into thin walled paper tubes of internal diameter 6.7 mm, one end of which is closed using fabric material similar to a cigarette filter. The packing is done uniformly by tapping the bottom end of the tube. This ensures even distribution of the powder all over the cylinder. However, since thin paper tube has been used, packing it with densities estimated as above resulted in tearing of the paper wall. Therefore, the densities of the packing inside the paper tube are slightly less; 338 and 336 kg m^{-3}, respectively, for teak wood and cow dung powders. The paper tube is marked along its length at uniform intervals of 10 mm. As mentioned earlier, three different orientations (vertical, horizontal and upside-down) are used. The atmosphere has been quiescent at a temperature of around 35°C. The time taken by the smolder front to travel a given length segment is recorded in each orientation for each fuel. The ash formed during the smolder process fell-off by itself after it accumulated over a particular length. Photographs at regular time intervals were captured for all the orientations. Experiments are repeated for at least 3 times to have consistent results.

RESULTS AND DISCUSSION

Fuel characterization: Thermo-Gravimetric Analysis (TGA) of powdered teak wood and cow dung under air atmosphere have been carried out using TGA Q500 V 20.10 Build 36 manufactured by TA instruments. The mass loss rate for a heating rate of 20°C per minute has been measured for each fuel. The % weight loss as a function of temperature is shown in Fig. 1.

Teak wood and cow dung powders have almost similar weight loss characteristics up to a temperature of around 180°C-weight loss rate of teak wood is slightly lower than cow dung, in this range, which is due to lower moisture content in teak wood. Teak wood has around 3% moisture, while cow dung has around 6.5%. Further heating-up to a temperature of approximately 400°C, teak wood suffers heavy weight loss of around 67.2% because of release of its volatiles. The volatile content of teak wood is much higher than that of cow dung, which has a value of only around 45.6%. Figure 1 also indicates that the fixed carbon content in cow dung

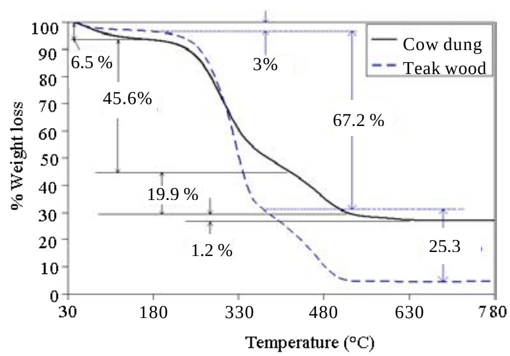

Fig. 1: Weight loss as a function of temperature

Table 1: Calorific values of teak wood and bio mass samples

Fuel	Heating value, kj kg^{-1}
Cow dung	13980
Teak wood	20461

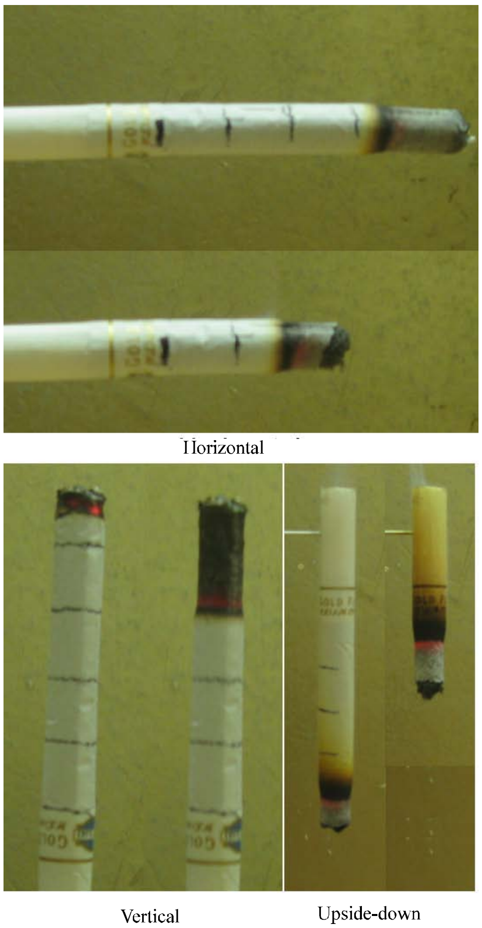

Fig. 2: Smoldering process for different orientations

is approximately 20%, while that in teak wood is around 25%. Furthermore, the ash content of cow dung (around 27%) is much higher than that in teak wood (around 4.5%). Calorific values of these fuels have been estimated using bomb calorimeter AC 500 manufactured by Leco Instruments. Table 1 presents the calorific values of cow dung and teak wood powders. The heating value of teak wood is similar to that reported in literature for saw dust (Roy *et al*., 2010). The calorific value of cow dung is higher than that reported for cow dung in literature (Roy *et al*., 2010), which may be due to environmental and aging conditions.

Smoldering combustion: Figure 2 presents the photographs showing the smoldering sequence of cow dung powder stacked inside a paper cylinder, kept in horizontal, vertical and upside-down orientations, at two different time intervals. The effective length of the paper tube packed with fuel powders is 50 mm. Smoldering rates are measured till the smolder front reaches 10 mm from the end of packing. As mentioned earlier, the ash that is formed falls-off by itself after accumulating for a certain length. Similar observation is made with teak wood powder as well. In the upside-down configuration, the smoke leaving the smolder front travels upwards, pre-heating the tube; this is indicated by yellow color of the paper. The smolder propagation does not happen at a uniform rate throughout the length, which may be due to several factors including the rate of oxygen diffusion and non-uniform particle sizes. Table 2 and 3 present the smoldering rates for different length segments along the tube for teak wood and cow dung, respectively.

In horizontal orientation, the hot gases resulting from smoldering combustion escapes in perpendicular direction to the paper tube, due to which, the further heating of un-smoldered powder is predominantly due to conduction and to some extent, due to radiation. It can be noted from Tables 2 and 3 that for horizontal orientation, for both fuels, the smoldering rate increases till the smoldering front reaches the start of the last segment. In the last segment, the smoldering rate either decreases, as seen in the cow dung case, or, remains constant, as seen in teak wood case. This may due to reduction in the effective surface area for oxygen diffusion and reduction in the combustible volume in the last segment.

In vertical orientation, the variation trend for the smoldering rate is random. The hot gases escape upwards, creating an induced air flow around the periphery of the paper tube. The ash formed accumulates for a certain length and falls-off by itself. For this orientation, the ash accumulation length is higher than the other orientations. When the ash accumulates, oxygen availability decreases and when it sheds-off, oxygen availability increases. Combined effects of the induced air flow and the ash present on the top of the smolder front causes this random variation of smoldering rate.

In upside-down orientation, for both fuels, the smoldering rate decreases as the length decreases. However, the initial values of smoldering rates are significantly higher for this orientation, when compared to the other orientations. This is because the hot gasses flowing upwards preheat the circular tube over its periphery along its axis. In this case, the smolder front and the hot gases move in the same direction. It may be noted that in the case of teak wood, the smoldering rate for the second segment on wards becomes much lesser than that for the corresponding segment in the other two orientations. But in the case of cow dung, the smoldering

Table 2: Smoldering rate for different length segments along the tube for teak wood

	Smoldering rate in mm/s for different orientations		
Length segment	Vertical	Horizontal	Upside-down
50-40	0.049	0.045	0.052
40-30	0.053	0.047	0.045
30-20	0.057	0.050	0.044
20-10	0.044	0.050	0.032

Table 3: Smoldering rate for different length segments along the tube for cow dung

	Smoldering rate in mm/s for different orientations		
Length segment	Vertical	Horizontal	Upside-down
50-40	0.057	0.052	0.071
40-30	0.054	0.053	0.067
30-20	0.058	0.059	0.060
20-10	0.064	0.056	0.047

Table 4: Average smoldering rate for 40 mm regression

	Smoldering rate in mm/s for different orientations		
Length segment	Vertical	Horizontal	Upside-down
Teak wood	0.050	0.048	0.042
Cow dung	0.058	0.055	0.059

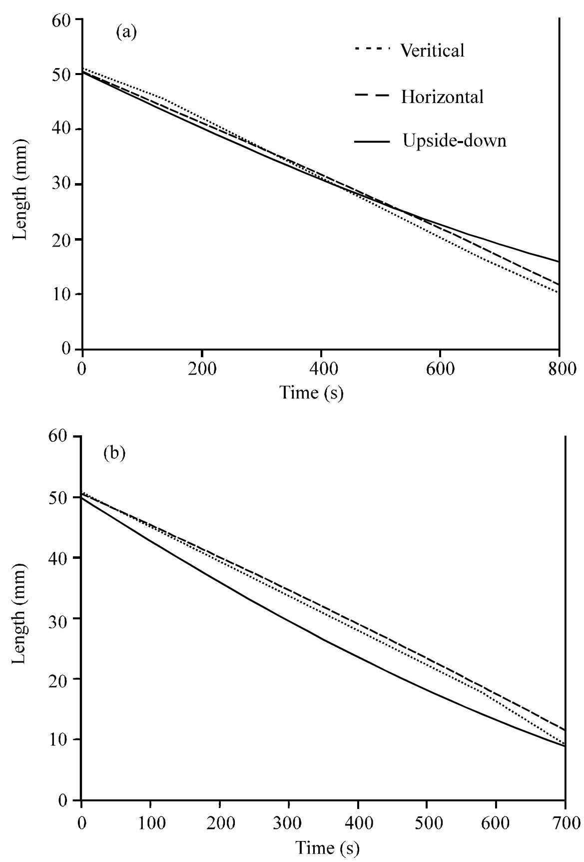

Fig. 3: Variation of length with time for paper tube stalked with powder of (a) teak wood (b) cow dung

rate of upside-down orientation is higher than the other two in first three segments even though it decreases significantly in the last segment. This can be explained by noting the amount of volatiles that each fuel as in Fig. 1.

For teak wood, within 400°C all the volatiles escape out. Therefore, preheating occurring in this orientation helps only to a little extent. For cow dung, volatiles continue to escape until a temperature around 520°C. Therefore, for this case, preheating by upward flowing hot gases helps in increasing the smoldering rate. In the last segment, as seen in earlier case, reduction in combustible volume and ash accumulation affect the smoldering rate.

The variations of length as a function of time for all three orientations are mentioned in Fig. 3. Figure 3a illustrates the variation of length for teak wood powder stacked tube. As discussed earlier, in the first 10 mm segment, the upside-down configuration has highest smolder rate. Vertical orientation takes over the upside-down case in second segment. The horizontal orientation has higher smoldering rate in the third segment than the upside-down orientation.

As mentioned earlier, due to release of volatiles within a temperature of 400°C, the preheating occurring in upside-down orientation does not help the smoldering rate for the teak wood case. However, for the cow dung case Fig. 3b, upside-down has the maximum smolder rate until the last segment. Preheating by upward flowing hot gases helps in this case.

Average smoldering rates, for 40 mm regression for each fuel and for each orientation are presented in Table 4. For both fuels, horizontal orientation has the least smoldering rate due to the fact the heat transfer that is accompanying the smoldering process is predominantly due to conduction and to some extent due to radiation. For vertical and upside-down orientations, the induced air flow parallel to the axis helps in increased smoldering rate, in spite of the accumulation of ash, which disturbs the oxygen penetration.

From Table 4, it is also clear that average smoldering rate is higher for cow dung. The possible reasons for this trend could be larger particle size of cow dung powder, its low calorific value, lower fixed carbon content and requirement of lower amount of oxygen and higher weight loss rate at lower temperatures.

CONCLUSION

An experimental investigation of smoldering combustion of teak wood and cow dung particles has been carried out. Fuel characterization analysis showed that cow dung has low calorific value than teak wood because of its lower volatile and fixed carbon contents. Smoldering combustion has been studied by igniting one end of the tube containing biomass particles and recording the rate of regression of the tube length. Average smoldering rate of cow dung has been higher than that of teak wood, basically because of lower fixed carbon content and requirement of lower amount of oxygen. It has also observed that, for cow dung, the orientation effect primarily dictates the regression rate; the upside-down configuration helps in preheating the particles by upward flowing hot gases and produces the maximum burning rate for that case. While, for teak wood, exactly opposite trend is observed because of it weight-loss characteristics with temperature.

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