

Fluidization and Combustion Characteristics of Pine Needles in Fluidized Bed Combustor: An Experimental Investigation

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Article Info Volume 83 Page Number: 5177 - 5189 Publication Issue: March - April 2020	Abstract Pine needle (PN) from the coniferous forest has enormous energy potential in Himalayan territories. The present study investigates the fluidization and combustion characteristics of PN in FBC. It is done in four steps: 1) Thermogravimetric Analysis (TGA) 2) cold-state characteristics 3) combustion tests 4) fly-ash analysis. At first, TGA demonstrates the physicochemical changes and confirms ignition, rapid devolatilization and combustion points for PNs. At second, Experiments on the cold-state show the mixing characteristics of PNs with silica sand indicates that the 3.00 mm PNs with 2% concentration mix well with bed material at fluidization number (FN=4). However, improper mixing was found because of little segregation above and below FN=4. Followed by the combustion tests (third step), in which the temperatures of the dilute phase region were found to higher than the combustion zone and secondary air have no significant effect on flue gas temperature. Additionally, the combustor had achieved combustor efficiency (η Combustion) over 73.19%. The ash related problem had not appeared at the operating temperature range
Article History	between 700-940°C for 16 hours. At last, the fly ash suggests the combustor performance
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Publication: 27 March 2020	Index Terms; pine needles, cold-state behavior, fluidized bed combustor, ash study.

I. INTRODUCTION

Biomass covers a wide range of different raw material (from agricultural, forestry and domestic) as fuels with distinct compositions and combustion appearance [1]. Mostly, biomass consists of alkali metals along with a high amount of hydrocarbons, volatile matter and low Gross Calorific Value (GCV) [2,3].

The most coniferous forests in the Himalayan territories cover 1.09 million km² have a considerable potential of PN (a waste product of pine tree, i.e., Pinusroxiburghii) [4,5]. PN is most occurring and promising resources can provide a sustainable option [6]. PN litters off from trees in

the middle of March to the onset of rain in July and lounge on the forest floor for a more extended period. Shed PNs have to make a thick layer of foliage on the pinewood floor, prevent natural growth of forest flora and also have relatively poor biodegradability due to high lignin content [7]. Moreover, dried PNs are the primary cause of forest fires in the summer days results in damaging the large forest economy [8,9]. There is a crucial need to emphasize the use of litter PN with an efficient available technique which can help to reduce air pollution and solve the disposal oriented problems. Among all biomass utilization techniques, fluidized bed combustion (FBC) is one of the best suitable available technology with excellent heat and mass,



fuel flexibility feature, etc. for converting biomass into a useful energy source. It becomes today's most promising technology which is inexpensive and providing adequate environmental control on hazardous emissions [3,10,11]. Most of the biomass cannot be effectively fluidized because of their unpredictable shape and size [12]. In the literature, various studies have been stated on the combustion characteristics of biomass in the FBC for commercial energy production [13–16]. The prior studies are also articulated the operating principle for various agricultural and municipal waste, although a small proportion has been discussed about the utilization of forestry waste in the FBC The present work focuses [17–21]. on the fluidization characteristics and combustion of unexploited PN source at various operating parameters. Furthermore, TGA and ash analysis provides additional reliable information of its biofuel properties

II. MATERIAL AND METHODOLOGY

The PNs were selected collected which found in Solan Forest Range, Himachal Pradesh, India (30.05°-31.15° north latitudes and 76.42°-77.20° east longitudes). PNs were solar-dried to remove the moisture content and further chopped in four different sizes (3 mm, 6 mm, 9 mm, and 12 mm) with the help of chopping machine for the cold-state fluidization.

A. Fuel analysis

PN powered samples were analyzed for the ultimate analyses, proximate analysis, lignocellulosic analysis, LGV, thermogravimetric method, and for elemental analysis using CHNSO analyser, (IS: 1350 (part-1) 1984, reaff. 2013, wet chemistry method, bomb calorimeter, PerkinElmer TGA-4000, and SEM/EDS technique. At last, the fly ash elemental analysis and ash fusion temperature were examined to predict the ash-related problems.

B. Experimental apparatus

Figure 1 and Figure 2 show the schematic diagram of the experimental setups for cold-state and fluidized bed combustor, respectively.



Method	Formulae		Deposition criteria
$\eta_{Combustion}[22]$		$100 - S_L$	The Siegert constant value for PN is 0.64.
	Where		

Table 1: Equations for predictive index



	S _L is the flue gas coming out of the stack is calculated by "Siegert Formula."	
	$S_L = k_s \times \left[\frac{T_{fg} - T_a}{CO_2}\right]$	
AI [23]	$\frac{K_2O + Na_2O}{SiO_2}$	$R_{b/a} > 1Low$ R _{b/a} $< 1High$
R _{b/a} [24–26]	$\frac{Fe_2O + CaO + MgO + K_2O + Na_2O}{SiO_2 + Ti_2O + Al_2O_3}$	< 0.5 Low R _{b/a} 0.5 – 1Medium > 1 High
SI [27]	$R_{b/a} \times S$	< 0.6 Low SI0.6 – 2Medium > 2 High
S _R [24,27]	$\frac{\text{SiO}_2}{\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3} \times 100$	$\begin{array}{ll} > 78 & \text{Low} \\ S_{R}66.1 - 78 \text{Medium} \\ < 66.1 & \text{High} \end{array}$
F [24,26]	$R_{b/a} \times (K_2 0 + Na_2 0)$	< 0.6 Low F0.6 – 40Medium > 40 High
IA [25]	$\frac{\text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{GCV}} \times \text{Ash(\%)}$	 > 0.7 probably fouling IA> 0.34 fouling is certain to occur > 2.00 No fouling
TA [25,27]	$(K_2 0 + Na_2 0)$	< 0.3 Low TA0.3 - 0.4Medium > 0.4 High
Q [28]	$\frac{\eta_{Combustion} \times B \times GCV}{100 \times 3600}$	$\eta(\%) = 100(\%) - S_L(\%)$
T _{AF} [25]	$\frac{4 \times IDT + HT}{5}$	
Chlorine (Cl) [24,26]	Weight percentage of Cl in an "as received" fuel sample	< 0.2 Low Cl0.2 - 0.5Medium > 0.5 High

III. RESULTS AND DISCUSSION

A. Fuel analysis

The results obtained from ultimate analysis, proximate analysis, lignocellulosic analysis, and

GCV for PN (as-received basis) are shown in Table 2. From the result of ultimate analysis, the composition of the PN has shown 48.20% carbon, 6.10% hydrogen, 38.30% oxygen, 0.12% sulphur, and negligible nitrogen. The observations agree the



From the proximate analysis, the percentage content of volatile matter for the PN sample was 75.75%. Ash was determined to be 3.45%, is the nongaseous, non-liquid, end product, mainly considered as the residue after complete or incomplete combustion. The volatile matter and ash content of PNs observed are acceptable. The fixed carbon content for the PN sample was determined to be 16.67%, which is the percentage of carbon available (not equal to C found in ultimate analysis) released as hydro-carbons (volatiles) during combustion.

The LA results of the PN sample are presented in _ Table 2. Lignin content refers to the most persistent organic molecule that is highly resistant to environmental deprivation after defoliation. However, PNs have 37.50% lignin content provides evidence that it has poor biodegradability due to the presence of benzene rings [7,31]. The remaining part comprised of cellulose around 53.46%, have exhibited huge concentration as compared to lignin – in the PN sample. The term holocellulose signifies the absolute cellulose, which is made out of cellulose and hemicelluloses.

The GCV value for the PN sample was measured as 18.64 MJ/kg. The value compares with ultimate analysis-based and PA-based correlations, calculated as 19.78 MJ/kg and 19.85 MJ/kg, respectively. There is no considerable distinction between the measured and determined values. Table 3 summaries the physical properties of the bed inventory.

Table 2: Properties	of PNs use	d in experiments.
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Parameter	Unit	PN		
Ultimate analysis ^a				
Carbon	%	48.20		
Hydrogen	%	6.10		
Oxygen ^b	%	38.30		
Sulphur	%	0.12		
Nitrogen	%	Negligible		
Proximate analysis ^c				
Volatile content	%	75.75		
Fixed carbon	%	16.67		
Ash	%	3.45		
Moisture content	%	3.83		
Lignocellulosic analysis				
Holo cellulose content*	%	53.46		
Lignin content	%	37.50		
Alcohol benzene	%	6.23		
extractives				
GCV	MJ/kg	18.64		
GCV _{UA}	MJ/kg	19.78		
GCV _{PA}	MJ/kg	19.85		
^a on dry ash-free basis				
^b by difference				
^c solar-dried basis				
* cellulose + hemice	cellulose + hemicellulose			

Table 3: Properties of silica sand.

Diameter	Particle	Bulk	8	ф
	density	density		
	(ρ_B)	(ρ_T)		
(µm)	(kg/m ³)	(kg/m ³)		
500	1540	2,963	0.5	0.9

The TGA of the PN is shown in Figure 3. The graph can be determined that there was a significant number of chemical and physical changes observed during the heating of the PN sample. Stage 1, the initial weight loss (up to 3.21%) is due to the removal of interstitial moisture content between



20°C to 112°C, is perceived as the drying stage. The moisture content also confirmed by ultimate analysis (as given in Table 1). The moisture content consumes more heat for drying during combustion.

Stage 2, the released volatile components such as char, gases, and tar, are released during the devolatilization. The maximum weight loss of 64.11% of the sample occurs between 200°C to 465°C temperature range. An active pyrolysis region was started at the ignition temperature (T_{ig}) of 204°C demonstrate the devolatilization zone. The T_{ig} of PN is the point on of the intersection of the DTG/TG curve. The decomposition of PN on the highest temperature peak at the devolatilization zone was measured 475°C, known as glass transition temperature (T_g).

Stage 3 is the char combustion zone, where weight loss of 12% was observed in the temperature range 465-536°C. Stage 4, the ash formation was perceived in the temperature range between 536-900°C containing around ~8% weight loss. About 0.9mg of biomass sample left behind in the form of char residue.

There are two DTG troughs, the first small trough was noticed in the temperature range between 30-150°C having a weight loss rate of around $\sim 2.67\%$ /min. In this region, the degradation of the low carbon content occurred together with the removal of moisture content, followed by the second significant trough region of the DTG graph. It shows the char combustion zone that formed in the temperature range between 150-580°C with the maximum weight loss rate around ~62.22%/min at 360°C. Thermal degradation of hemicellulose and cellulose typically occurred at the temperature range between 250-500°C, respectively. After 580°C, there is a slow rate of mass degradation ~6%/min was due to the small amount of char combustion. There is no large trough appeared beyond 580°C, because maximum PN content has degraded, and little thermal instability was due to the presence of char residue (ash content).

Figure 3 also represents the DSC curve showed the exothermic and endothermic heat effect. It gives the necessary information to heat the PN sample and heat evolved during reaction. The ratio of heat flow per unit mass with different temperature has a broad peak in the temperature range of 115-550°C show the exothermic reaction between reactants. The devolatilisation and partial char combustion occur in this region. It results in heat evolves due to volatile matter and combustion of unburnt particles. It also ensures the breakdown of large hydrocarbon chains and thermal degradation of the PN particles into gaseous products.

B. Mixing characteristics

Figure 3 (a, b, and c) shows the binary mixing characteristics of four different lengths and three different concentrations of PNs with silica sand. Following are the experimental conditions consider for experimentation: silica sand effective diameter 500 μ m; PN concentrations 2%, 6%, and 10%; PN lengths 3.00 mm, 6.00 mm, 9.00 mm, and 12.00 mm; and fluidizing velocity 2.2 m/sec. The PN particles of all size were mixed in various proportion as varying the concentration. As evident in the figure, PN concentration and size has a more









Figure 3: PNs mass fraction profiles. (a) PN with 2% concentration. (b) PN with 6% concentration. (c) PN with 10% concentration.

significant impact on the mixing characteristics. It can be noticed, 3.00 mm and 6.00 mm PN particles has shown good fluidizing behavior and mix well with silica sand. Experimentation of PN mass distribution in the cold fluidized bed showed that the large PN particles during processing, interacted with bed material and the bubbles in the bed have appeared the emulsion zone. The presence of PN particles outside the emulsion zone evidenced the successful distribution in the fluidized bed.

Fig. 4(a) represents the effect of fluid velocity on the mixing characteristics of PNs. Following are the experimental conditions considered for the experimentation: silica sand effective diameter was 54.95 µm, the percentage mixture of PN was 2 wt% and 3 mm PN. From the figure, at lower fluidizing velocity (N=1.4) the little turbulence has resulted in the poor mixing of PNs. By further increasing the fluid velocity up to N=2.0, the chamber expands quickly, and the formation of the enormous bubbles blow up at the bed surface provide the space to PN particles to get inside the bed. As the fluidizing velocity increases the PN particles get down into the bed and therefore, more uniformed mass fraction distribution along the bed height was found. It is

concluded that more significant mixing characteristics will exist at high fluid velocity. Instead of that when the fluidizing velocity beyond 2.3 m/s (N=5.2), there will exist a discontinuity as comparing to lower fluidizing velocities. This can be clarified that at the fluidization number higher than 5.2, all the lighter PN particles will be blown off and become easily elutriate, which never blend in with the silica sand particles of the bed. So, the fluidization number from 2-5 become more appropriate for even distribution. The flattened surface of the mixture after sudden stopping the fluid flow at between FN=3-4.1. It has confirmed the existence of uniform distribution of binary mixture.

Fig. 4(b) shows the effect of wt% of PN particles in the blend on the binary mixing characteristics. Following are experimental conditions were used for experimentation: the effective diameter of silica sand was 54.95 μ m; fluid velocity was 2.2m/s and consider 3mm PN length. As the information can be perceived from the figure, there will be tiny segregation exist when the PN wt% increased.



(a)





Figure 4: (a) Effect of gas velocity on PN mass fraction distribution with 2% PN concentration. (b) Effect of the mass percentage of PN. (c) U_{mf} of wt% used.

The present study has also discussed the effects of needles like shape and their densities on the minimum fluidization velocity U_{mf} . The four different PNs lengths having the non-spherical shape and different densities were ranged from 139–292kg/m³. There is no satisfactory equation are available in the literature for predicting U_{mf} for the binary mixture. The U_{mf} obtained from the

experiments were plotted in Fig. 8. It shows the plot of bed pressure drop (ΔP) across the distributor plate against the superficial velocity (U). Initially, ΔP and the U shows the linear relationship during fluidization of the packed bed at a stagnant height of 68mm. After that, there is a reduction in the elevation of the graph with the increase in the U. This trend is observed with all four samples of PN. It is because the bed mass of different length of PN particles has counterbalanced by drag force exerted by fluid flow during fluidization. Ergun well-defined the drag force exerted by flowing fluid along with U_{mf} is equivalent to the weight of bed [32]. During experimentation, when initial stagnant heights of the bed were changed, the U_{mf} also slightly changed for different lengths of PNs (Escudero&Heindel, 2011 [33]). Therefore, initial stagnant bed height does exert the noticeable impact on the fluidization of PNs.

The values for 3.00 mm and 6.00 mm of PNs have slightly lower than theoretical results else ways for 9.00 mm and 12.00 mm have little higher. The voidage during the packed region of a fluidized bed increased with increase in the length of PNs. There was the formation of big voids instantly as increased in the U across the bed. This is for the fact that some portion of fluid by-pass the PNs by flowing from the free channels inside the bed. Further, the figure suggests that U_{mf} increased with increase in the PNs length. It is due to the influence of gravitational and inter particle friction forces were more significant for bigger PNs as compared to a smaller one.

PN density is another essential contributing factor quantified the fluidizing characteristics. With three different wt% of PNs in the bed, the initial stagnant bed heights were 138 mm, 153 mm, and 165 mm. The U_{mf} of the mixtures of three different PN particles and silica sand (d_p = 500 µm) are shown in Figure 5. Comparison graph shows the 10 wt% of PNs.





Figure 5: The Δ P-U curves of different PN size.

C. Combustion tests

The cold state optimum parameters were further test for the combustion to examine whether FN between 2 to 5 can have steady-state combustion of PN, without the fluctuation of bed temperature. The combustion of the bed results in the net increment of the temperature of the bed at the freeboard region instead of the bottom zones. This is due to the fact that silica sand could hold the gaseous part of the released from the combustion of PN in the densepacked part [34]. Later, the temperature profiles along the vertical direction demonstrated that most of the volatiles contents of PN particles are burnt in the freeboard regions of the combustor. Figure 6 shows the temperature profiles in the bed material and freeboard under a fuel feed rate of the 16 kg/hour. After neglected the 7% to 20% elutriate pine needles in FN range from 2 to 5, the average carbon content in the ash reduced to 10.34% from 18.42% (by wt%).

During the combustion of PN, it results in the smoky flame at the exit. So, it is essential to check the exit gas for pollutant emission that contaminate the environment. The investigation of the flue gas was done on the exiting part of the cyclone used for the ash collection. Simultaneously, Testo 350 professional portable gas analyzer was used to measure the concentration of CO₂, CO, NO_x and SO_x . The relative errors are supposed to be 1% for Oxygen and 3-5% for other gases. Table 4 suggests the concentration of flue gas emission profiles at different operating conditions. The PN ignition starts 517°C. where the particles experienced at devolatilization and evolved the volatile matter gases while entering into the combustor, mixed with the high-temperature silica sand results in combustion. Therefore, CO concentration increased when the secondary pours are remained open. The highest gas concentration was achieved about 2,298 ppm on FN=2, while the lowest CO concentration occurred about 47 ppm on FN=4 at the exit. The combustion results show that CO emission generally varies between 295-47 ppm, NO_x varies from 136-183 ppm, and SO_x varies from 32-54 ppm. The NO_x formation during the combustion is reasonably low because it contains a very less amount of N (negligible) as confirmed by proximate analysis shown in Table 2.



Figure 6: Temperature profiles.

Table 4: Emissions of PN combustion.

FN	СО	CO ₂	SO _x	NO _x	Н	Р
	(ppm)	(%)	(ppm)	(ppm)		(MJ/h)
2	295	12.34	35	136	71.53	0.09
3	460	10.92	46	155	75.21	0.10
4	497	13.78	54	183	74.92	0.11
5	336	11.67	32	165	71.10	0.09



The ash management during and after combustion is the biggest challenge, results in the unscheduled shutdown of the combustor. The major intractable problems include slagging, fouling, agglomeration, and ash disposal which directly influence the combustor efficiency [35]. The combustion experiments show no indication of an ash-related problem at contemplated operating conditions of the FBC. The presence of different elements in the ash formed, elutriated out of the combustor help to understand the mechanism of forming agglomerates and slags, commonly responsible for de-fluidization. Table 5 shows the composition of the fly ash when operated at different functional conditions. Figure 7 show the elemental composition. Table 5 shows the as fusion temperature of fly ashs.



ash.

Table 5: Four different ash-fusion temperature.

Ash fusion temperature	°C
Initial deformation temperature (IDT)	1255
Softening temperature (ST)	1274
Hemisphere temperature(HT)	1280
Fusion temperature (FT)	1298

According to Table 1, the concentration of the total alkali metal content is high (generally Na and K) in

the PNs promote fouling (high tendency) and unmanageable stiffs of alkali induced, coating induced, and melt induced (at fusion temperature) slagging's. The different elemental concentration of the alkali, alkali earth metal (Mg, Ca), and less reactive metals (Si, Al) responsible for the agglomeration at various intricate chemical reactions during combustion. Further, the work has to be extended to comprehend the ash characteristics at high temperatures is determined by AFT analysis. The PN fly ash collected in the study contained a high concentration of SiO₂ (19.57%), CaO (21.93%), and Fe₂O₃ (22.22%). the P₂O₅, Na₂O and K₂O are the three oxides that have a low melting temperature, start to deform after 700°C. These oxides provide an initial sticky surface on the Si particles, bed material and other ash particles formed small, week, and unstable agglomerates. The low concentration of theses oxides has less tendency to form agglomerates in PN ash. Equation 6 also validates the AI for PN is calculated as 1.17, which is greater than 1, reveals that the agglomeration formation at the given temperature range is low.

Alkali transformation and alkali-induced slagging are occurred generally due to the presence of elements such as Si, S, Al, and K. Chang et al. [36] have suggested IA for biomass to account for slagging and fouling. For PN, less formation of the fouls and low to medium tendency of slags suggested by equations of IA and SI, respectively (as shown in Table 1).

IV. CONCLUSIONS

In this study, the fluidization and combustion characteristics of PNs were studied experimentally. Following conclusions from the study can be drawn:

• PNs have evidenced to be surpassing forest biomass with outstanding biofuel properties such as significantly high GCV of 18.64 MJ/kg and a low ash content of 3.45%. The immense volatile matter of 75.75% adds desirable merits in the combustion characteristics has motivated to use PN source



through FBC.2

• The thermal degradation of PN was examined by performing TGA. It contains four main stages, drying (90-112°C), devolatilization (112-465°C), char combustion (465-536°C), and char combustion carbon removal (536-900°C). PNs highly volatile and easily ignite at low temperature (Tg=465°C).

• The mixing characteristic of the blends of PNs and silica sand has been investigated. It has been done to achieve optimum values by varying length of PNs, its concentration and U. It is found that 3.00mm length with 2% concentration of PNs has shown good fluidizing as well as mixing characteristics at FN= 4-5. The mixing characteristics decreased and U_{mf} increased with an increase in the PN length due to the low density of blends with bed material.

• The combustion of 3.00 mm PNs has been studied in FBC along with silica sand as a fluidizing medium. The maximum bed temperature has been obtained T=940°C, indicates proper fluidization during combustion. The released volatiles start burning in the freeboard region, achieved the temperature higher than the combustion region for all FN=2-5. The operating condition of FBC has been achieved average CE of 73.19% with a thermal output of 0.09 MJ/h.

• The agglomeration, slagging and defluidization occurrence in FBC of PNs were showed a low tendency of agglomeration up to an average operating temperature of 860°C. PNs have lowmelting alkali element content-rich fly ash such as Mg, Ca, K, P, and Si generally form unstable agglomerates which deform when reaching to high temperature. The ash-related problem may occur at the FT=1298°C determine by AFT test, where the substantial probability of coating of molten ash on the surface of silica sand will occur in FBC.

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ABBREVIATIONS AND ACRONYMS

Abbreviations:	Symbols		
AFT: ash fusion test	ΔP : pressure gradient		
	(Pa)		
AI: agglomeration	ks: fuel-specific factor		
index			
CE: combustion	R _{b/a} : base/acid ratio		
efficiency (%)			
DTG: differential	S _L : siegertconstent (%)		
scanning calorimetry			
EDS: energy dispersive	S _R : slag viscosity index		
X-ray spectroscopy			
F: fouling index	T _{AF} : temperature of ash		
	fusion		
FBC: fluidized-bed	T _{fg} : flue gas		
combustor	temperature (°C)		
FN: fluidization	U: superficial velocity		
number	(m/s)		
FT: fusion temperature	U _{mf} : minimum		
(°C)	fluidization velocity		
	(m/s)		
GCV: gross calorific			
value (MJ/kg)			
HT: hemispherical	Greek symbols:		
temperature (°C)			
IA: alkali index	ε: voidage		
IDT. initial	φ: sphericity		



deformation	
temperature (°C)	
LA: lignocellulosic	η: efficiency (%)
analysis	
PA: proximate analysis	$\rho_{\rm B}$: bulk density
(%)	(kg/m^3)
PN: pine needle	$\rho_{\rm T}$: true density (kg/m ³)
SEM: scanning	
electron microscopy	
SI: slagging index	
ST: softening	
temperature (°C)	
T _a : ambient	
temperature (°C)	
T _{ig} : ignition	
temperature (°C)	
TAO: total heat output	
(MJ/h)	
sTGA:	
thermogravimetric	
analysis	
UA: ultimate analysis	
(%)	

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