Project Completion Report on Torrefaction of Bamboo

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Acknowledgement

ABETS, CGPL, IISc expresses sincere thanks to National Mission for Bamboo Application (NMBA), Department of Science and Technology (DST), Govt. of India under whose auspices this project entitled “Torrefaction of Bamboo” has been successfully carried out.

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Executive Summary

This project was taken to enhance the storability of bamboo and also generate a product which can be a cheaper substitute for applications where black charcoal is currently being used. Bamboo is a fast growing fibrous plant grown in abundance the country. In India, one particular species of bamboo namely 'Melocanna baccifera', estimated to represent over a sixth of the country's growing stock of bamboo, is facing the threat of gregariously flowering between 2004 - 08. The flowering of Melocanna Baccifera is an event of great significance wherein large tracts of land are affected, as bamboo forests burst into bloom and then die. This sudden death of bamboo in huge quantity is expected to significantly increase the rodent population and therefore there is an urgent need to identify ways and means by which several tons of bamboo could be put to effective use in short span of time. So there is definite need to immediately use or preserve or extend the shelf life of the bamboo. The current practices of bamboo usage can only consume a part of the excess bamboo generated on account of this gregarious flowering thereby opening possibility for other usages. Torrefaction of bamboo is seen as one such possibility that apart from energy densification makes the product resistant to fungal attack thereby enhancing its storability.

Under the project sponsored by NMBA, DST, Govt. of India, torrefaction of bamboo has been successfully attempted wherein trails have been conducted in a kiln of 1 ton/day input capacity. Prior to conceiving the design of the kiln, basic studies have been conducted wherein the effect on torrefaction temperature (180 to 350° C) and residence time has been thoroughly investigated. The torrefied bamboo has been characterized for calorific value and elemental balance such as carbon, hydrogen and oxygen. Based on the analysis it is found that there is an enhancement in energy density by 20% against green bamboo between torrification temperatures of 250 and 260° C. The effect on residence time both on energy density and yield is found to be marginal. Apart from energy densification, torrefaction process makes the material hydrophobic, the moisture absorption over a long duration of observation is found to be between 3 and 5% against 10 and 12% with sun dried bamboo. The product from the process of torrefaction is referred as '*Grey Charcoal*"

The thermal energy required for torrefaction process is derived from 'green energy fuel' – generated from the gasification of bamboo and its waste. The kiln is designed to allow re-circulation of hot flue gases thereby making the torrefaction process efficient. The volatiles released in the process of torrefaction is fed back to the combustion chamber thereby making the entire process clean and does not contribute to atmospheric pollution. This batch-type kiln has completed successful trials at the laboratory is being shifted to Nagaland Bamboo Development Agency, Dimapur, Nagaland for field trials.

This consolidated report contains details of exploratory work, lab scale plant and pilot plant of 1 ton/day. The last chapter contains plant dimensions for 10 and 20 ton/day throughput. As a part of the project it was felt appropriate to conduct a survey on the current charcoal/activated charcoal consumption in North-Eastern states of the country. This was expected to provide input on the volume of charcoal traded and the possibility of replacing it with grey charcoal generated from bamboo. As the survey didn't elicit much response this aspect is not reported here. However, economics based on 1 ton/day plant is brought out.

Background of the Project

Bamboo is a fast growing fibrous plant grown in abundance in India. It is a versatile material finding usage in structural, construction, wood substitute, composite and energy production. In India, one particular species of bamboo namely ‘Melocanna baccifera’, estimated to represent over a sixth of the country’s growing stock of bamboo, is facing the threat of gregariously flowering between 2004 and 08. The flowering of Melocanna baccifera is an event of great significance wherein large tracts of land are affected, as bamboo forests burst into bloom and then die. This sudden death of bamboo in huge quantity is expected to significantly increase the rodent population and therefore there is an urgent need to identify ways and means by which several tons of bamboo could be put to effective use in short span of time. So there is definite need to immediately use or preserve or extend the shelf life of the bamboo. The current practices of bamboo usage can only consume a part of the excess bamboo generated on account of this gregarious flowering thereby opening possibility for other usages. Methods need to be devised to capture as much of this material for productive uses of the society. Several approaches are already under consideration at present. Torrefaction of bamboo is seen as one such possibility that apart from energy densification makes the product resistant to fungal attack.

Torrefaction is mild pre-treatment of any biomass (including bamboo) at a temperature between 200 and 250° C. During torrefaction the properties of bamboo undergo changes, wherein the end product has much better fuel quality compared to biomass for combustion application. The decomposition reactions during this process results in bamboo becoming completely dry and loose its tenacious structure, also the hygroscopic nature of the biomass is changed to hydrophobic material. Besides this, the process increases the calorific value of the end product. The actual weight loss in this period would be about 20 to 25 % whereas 90 % of the energy of the parent dry material is preserved in the torrefied matter. The combustion process of this matter has less problematic volatiles and hence the process is closer to that of charcoal. It can therefore be used as an alternate to charcoal in many applications. It also makes the material immune to attack by fungi. Hence long term storage without degradation is possible.

A project to enhance the storability of bamboo has been sanctioned by NMBA. This exploratory and development work has been carried out at Combustion Gasification and Propulsion Laboratory, IISc, Bangalore. The duration of the project was for nine months and involved exploratory work and development of a 50 kg/hr pilot scale equipment for the manufacture of torrefied bamboo. The objectives the project is briefly given below:

1. Conduct tests on a pilot scale version to establish the design parameters and characterize the principal properties with bamboo from selected sites

2. To provide the design details of a large scale system (to handle15000 to 17000 tonnes per year of as-received bamboo) for its establishment at one location and conduct tests to prove the performance at the field level

3. Establish the techno-economics of this approach.

Introduction and Literature Survey

Torrefaction involves mild treatment of biomass between 200 to 300° C in an inert atmosphere. Untreated biomass particularly agricultural waste has low energy density, high moisture content. These features make transport relatively expensive. Just drying would be insufficient as the biomass can regain moisture and rot during storage. Increasing the energy density such as torrefaction process can be seen as an attractive proposition. The product of torrefaction process is a solid product, which is torrefied biomass, has attractive properties such as improved heating value, low moisture content and ease of size reduction. The properties of torrefied biomass are as follows:

1. Lower moisture content and therefore higher heating value compared to biomass, Due to lower moisture content, it is cheaper to transport the torrefied biomass
2. Hydrophobic nature: the material does not gain humidity in storage and therefore unlike charcoal and biomass, it is stable and is resistant to fungal attack.
3. Easy burning and less smoke formation when burnt
4. Suitable for various application such as for cooking fuel, residential heating, raw material for manufacturer of fuel pellets, reducer in smelters - steel industry, manufacture of charcoal or activated carbon, gasification, co-firing with other fuels in boilers etc.

Literature does not contain information on bamboo torrefaction per se, nevertheless there is large amount of research conducted on biomass torrefaction. Research as early as in 1930 is reported in France, but there does not seem to be any publications available. Research work on torrefaction at a fundamental level has been reported by Mark J Prins [1] in his PhD thesis entitled “Thermodynamic analysis of biomass gasification and torrefaction”, however it does not contain details of industrial torrefaction process technology.

Literature reports that in the 1980’s, a commercial plant with a capacity of 14,000 ton/year was operated in France for the production of barbecue fuel [2], but the plant is no more in operation. Similarly Bourgois and Doat [3] have published torrefaction work using two tropical wood samples. This research is reported to have resulted in the building of a continuous wood torrefaction plant in 1987, the torrefied wood was used as a reducer in the production of silicon metal.

Bergman et al [4] reports the benefits of torrefaction process in terms of reduced electricity requirement for size reduction and production technology for the production of pellets. Similarly Pach et al [5] discusses the torrefaction process performed in a laboratory unit using two species of wood, birch, pine and sugar cane bagasse.

The above compiled literature study clearly reveals the work done at the fundamental level but there is no information about industrializing the process. Since the mandate of the project taken up involved development of a pilot scale plant, the current work was more focused on development and less on basic research work. The available information in the literature was used as guidance in realizing of the goal.

List of Reference:

1. Mark J Prins, Thermodynamics analysis of biomass gasification and torrefaction, PhD thesis, Technical University Eindhoven, 2005.

2. Girard P, Shah N, Recent developments on torrefied wood, an alternative to charcoal for reducing deforestation, REUR Technical series 20: 101 – 114

3. Bourgois J P , Doat J, Torrified wood from temperature and tropical species, advantages and prospects In: Egneus H, Ellegard A, Bioenergy 84, London, Elsevier Applied Science Publishers, p 153 – 159.

4. Patrick C A Bergman and Jacob H A Kiel, Torrefaction for biomass upgrading, 14th European Biomass Conference and Exhibition, Paris, October 2005.

5. M, Pach, R Zanzi and E Bjornbom, Torrefied biomass a substitute for wood and charcoal, 6th Asia Pacific International symposium on combustion and energy utilization, 2002.

Exploratory Studies

The first phase of the activity involved conducting lab scale studies and establishing of design parameters for scaling-up activity. Towards this a 100 kg/hr (based input feed capacity) was designed and tested in the laboratory. Prior to commencement of this work, exploratory work was conducting in identifying the temperature regime for torrefaction of bamboo. A series of experiments were conducted where the bamboo sample was subjected to temperatures between 100 and 250° C in an electrically heated oven. The bamboo species used for experiments was 'Bambusa bambos', - a thorny bamboo and one of the three major species of the country, extensively found in Central and Peninsular India - with a preference for rich and moist soils. These weigh about 3.0 – 3.5 kg/m and are shown in Plate – 1.

Plate 1: Bambusa bambos - Thicker variety bamboo sourced from the neighboring market

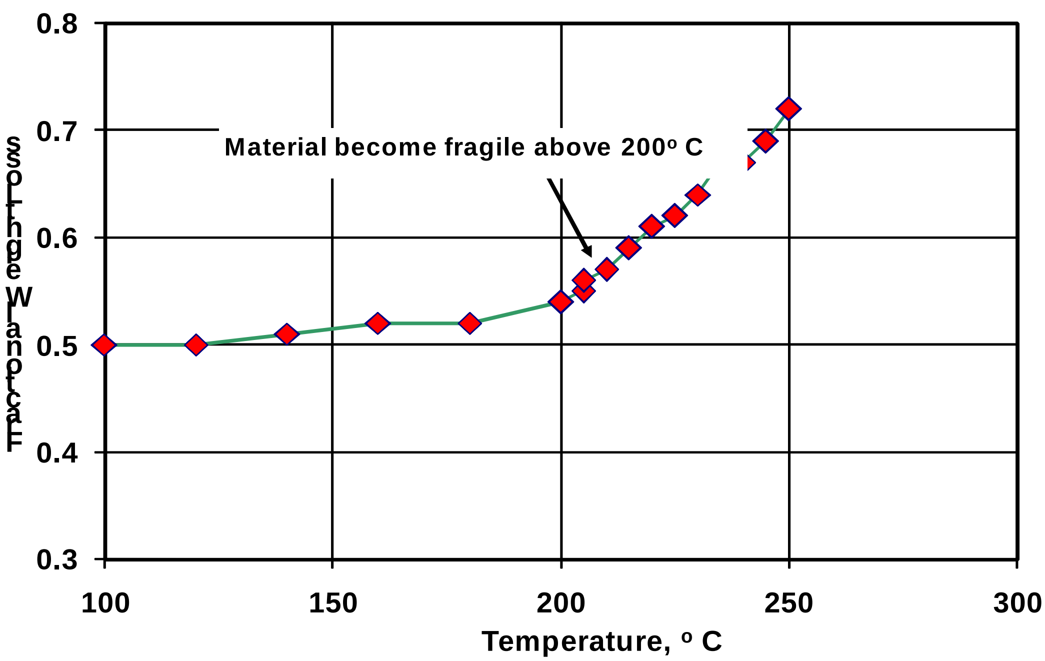


Fig. 1 Fractional weight loss vs Temperature, torrefaction regime for bamboo identified.

The results of the experiments are shown in Fig. 1. It is evident from the results that the critical temperature regime for torrefaction of bamboo is around 200° C. At about 200 – 205° C, the bamboo looses its tenacity and becomes fragile in nature. The bamboo samples during various stages of heating between 100 and 210° C is shown in Plate – 2.

Plate 2: Bamboo samples during various stages of heating. At about 205° C the bamboo losses its tenacity and becomes brittle, indicating bamboo is torrefied

Laboratory Scale Studies

A laboratory scale plant with an input feed capacity of 100 kg/hr (batch type) was built for the initial trials. The heat source for torrefaction was obtained by combusting producer gas + air mixture in the combustor. The producer gas was in turn generated in a gasifier system using waste wood as the feedstock. The hot gas temperature at the entry to the torrefaction chamber was maintained at varying temperatures between 200 and 350° C. The combustor and the torrefaction chamber were fitted with thermocouples to record the bed temperature in the chamber. To enhance the efficiency of the torrefaction process the hot flue gas was recirculated. The combustor, torrefaction chamber, blower and all connecting ducts were insulated to reduce heat loss. The schematic of the torrefaction process is shown in Fig. 2. The photograph of the lab plant is shown in Plate 3 and 4.

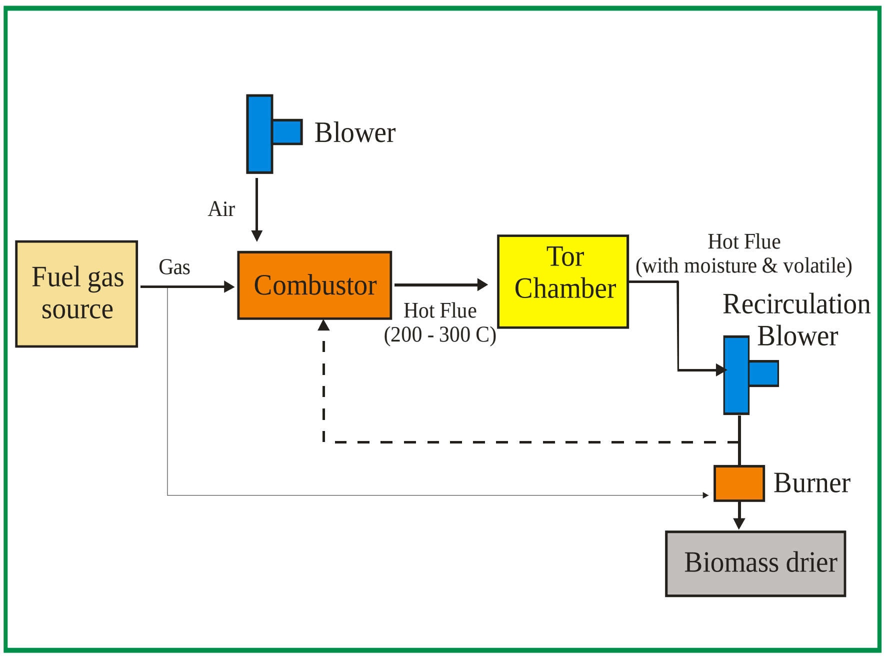


Fig. 2 Schematic of Torrefaction Process

One of the most important parameters that were to be established in the above process was the residence time. The only sure way of determining this was through experimental trials. Therefore experimental trials were conducted using cut green bamboo of 0.6 m length (50 – 60 mm diameter) with an initial moisture content between 9 and 47 % (on wet basis). Two types of bamboo, namely thin and thick bamboo were tried for experiments. Most of the trials were conducted using thin bamboo (Bamboosa-Bamboosa species). About 5 tons of Bamboo was procured for these trials from Dandeli forest in Karnataka. These bamboos measured about 6 m length with a mean diameter of 80 – 140 mm at the bottom to about 50-80 mm at the top. The typical wall thickness was about 10 mm. The moisture and ash content of the green bamboo was about 47% and 2 % on wet basis respectively.

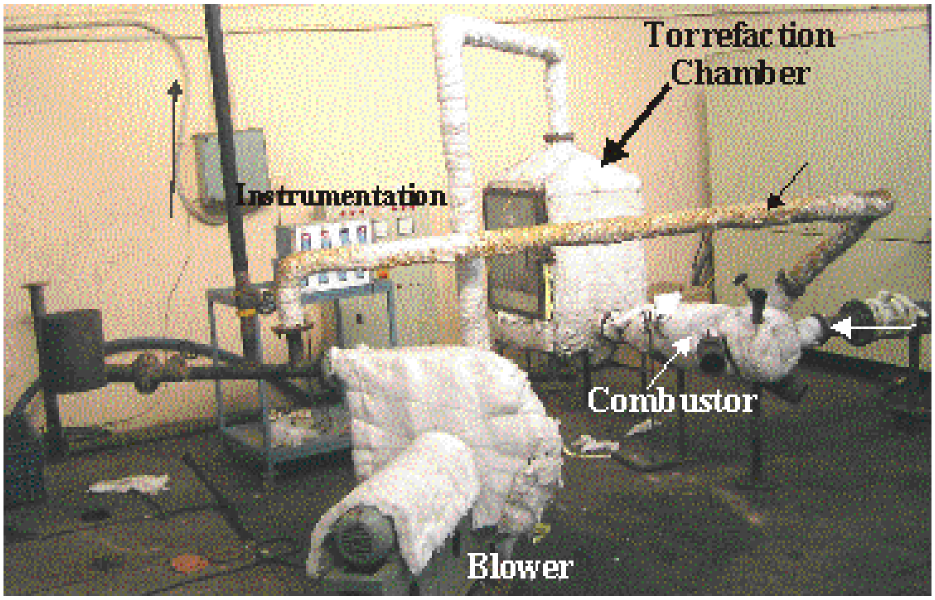


Plate 3: Laboratory Scale Plant Arrangement for Torrefaction Process

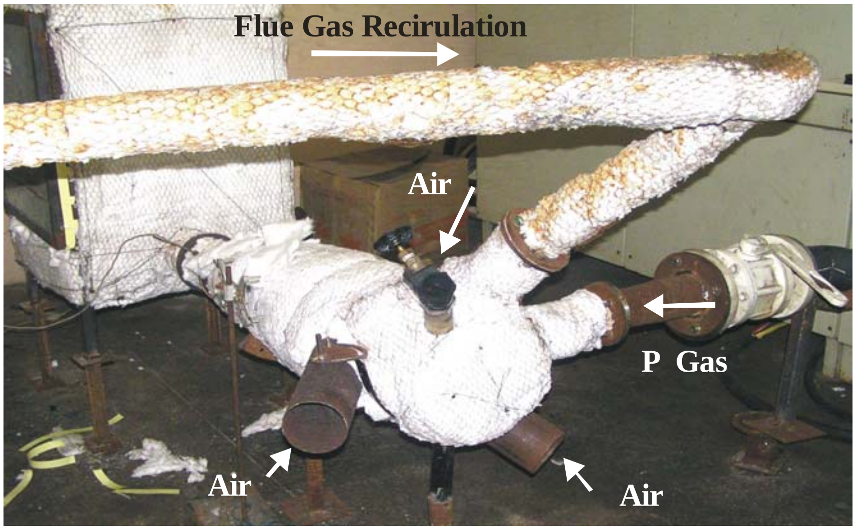


Plate 4: Combustion Chamber for Generation of Hot Flue Gases for Torrefaction Process

Raw Bamboo (50% Moisture wb)

↓

Bamboo Post-drying at 100° C

↓

Torrefied Bamboo

Plate 5: Bamboo during various stages - lab scale testing

It took about 2 to 3 trials to establish the operational procedure. During these exploratory trials the combustor was operated at power level of about 20 – 25 kWth. The hot gas entry to the torrefaction chamber was maintained at about 200 to 225° C. First set of experiments were conducted in non-recirculation mode and the dryer efficiency was found to about 7%. This was followed by experiments in part-recirculation mode wherein the operation was carried for about 3.5 hours, the efficiency of system turned out to be about 14%. The process was further optimized wherein the flue gas recirculation rate was increased such that there is no flame quenching in the combustor, this resulted in an efficiency of about 30 - 35%.

Further trials were conducted between temperatures of 200 and 350° C and at varying residence times (1- 3 hours). Other than maintaining of flue gas temperature at the entry to the torrefaction chamber, roughly inert conditions (oxygen < 2- 3%) were maintained at all times in order to prevent combustion of volatiles/biomass in the torrefaction chamber. The temperature during the torrefaction process was continuously monitored by recording the bamboo temperature at three/four tiers. In each of the tier, one bamboo had a provision for thermocouple insertion. Thermocouples were inserted to measure the surface, pulp and core on each of the identified bamboo. During the initial process there was large variation observed in temperature at various levels and also temperature within the bamboo. With time the non-uniformity used to reduce and by the time of completion of the trial the temperature was more or less uniform (variation by about 25 C). Upon achieving of the desired temperature by the top tier bamboo, the trial was stopped.

On the whole more than thirty trials were conducted and results of important ones are summarized in Table 1. It is evident from the Table that as the operating temperature is increased the loss of volatile matter is higher and consecutively the yield of solid matter is lower. The dependency on temperature appears to be much stronger than the residence time. In the temperature range of 180 to 220° C, the yield of solid matter is about 83% and as the temperature is increased to 350° C, the yield comes down to about 45%. The solid yield at varying torrefaction temperature is summarized in Table 2. The residence time at higher temperature is lower in some case because of initial moisture content being low in the raw bamboo. Lower initial moisture content would therefore need lower residence time.

There was inconsistency in the results of some of the trials due to incorrect estimation of initial moisture content in the bamboo. Initial estimation of moisture content had become some what problematic as there some variation observed in the moisture content along the length of the bamboo and moreover the procured green bamboo started to loose moisture. Therefore getting the right representative sample for estimating the initial moisture had become difficult. This was resolved in the subsequent trials by adopting a more elaborate procedure.

Fig. 3 shows the temperature profile at the exit of the combustor and the entry of the torrefaction chamber – grate entry, The temperature of the flue gas is maintained between 220 and 250 °C right through the process. The flue gas exit temperature slowly increases from ambient to about 230 °C by the completion of the process. Similarly Fig. 4 shows the temperature profile measured at three locations within a given bamboo – surface, inner and hollow. It is evident from this figure that the heating rate is between 0.5 to 1.0 °C/min. The temperature throughout the cross section of a given bamboo is more or less uniform at any point of time through the process. This uniformity in temperature ensures generation of uniform and consistent product.

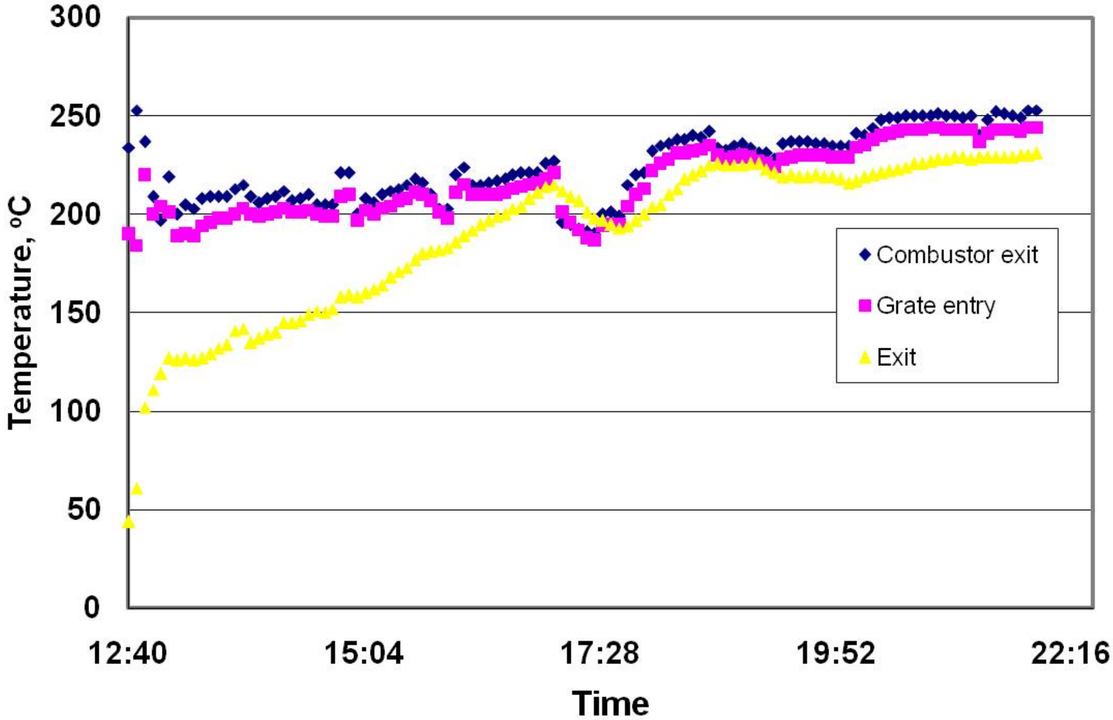


Fig. 3 Temperature at various points in the chamber during the process

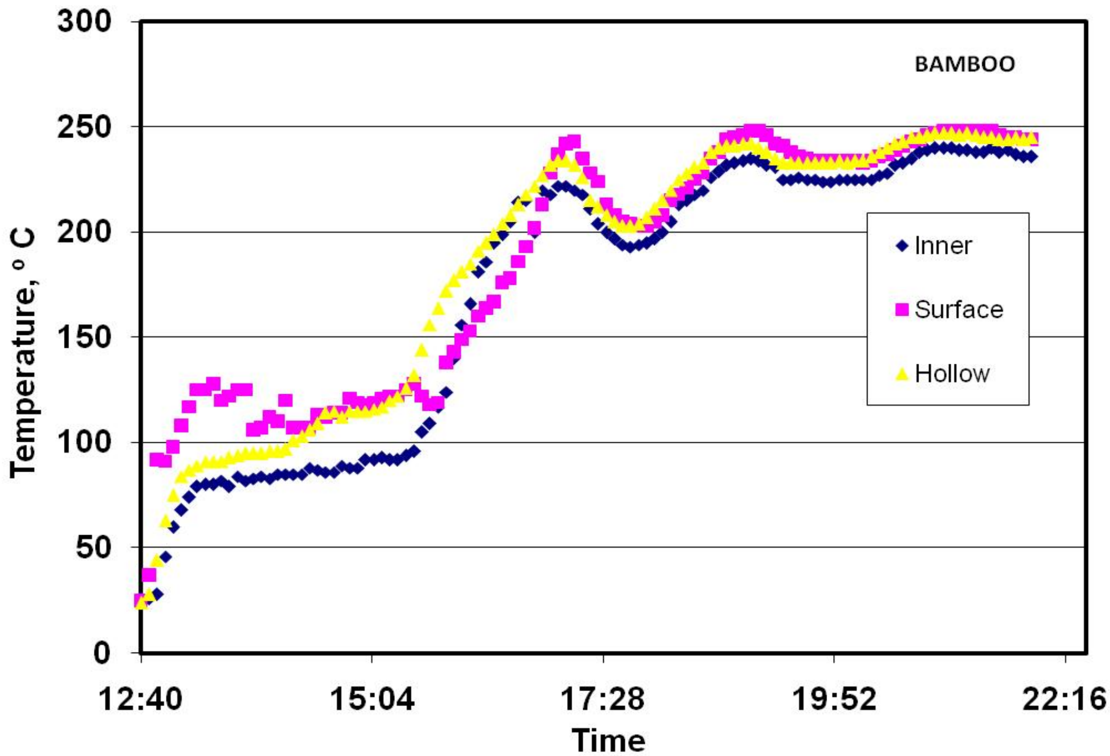


Fig. 4 Temperature in the bamboo during the Process

Table – 1: Summary of the Lab Studies

Bamboo	volatile loss	solid yield	Total Duration	Temp	Duration > 180° C
	%	%	Min	°C	hour
thick	15	85	525	207 -222	1
thin	17	83	400	199 - 222	1
thin	17	83	310	190-219	2
split	17	83	280	188 -216	2.5
thin	*42*	*58*	*250*	*196 -223*	*1*
thin	*39*	*61*	*375*	*213 - 222*	*3*
thin	22	78	400	232 - 236	3
thin	29	71	555	230 - 248	6
thin	30	70	380	230 - 248	6
thin	57	43	320	300 - 325	2.5
thin	28	72	205	250-283	2
thin	47	53	110	225-280	2
thin	37	63	180	270-300	1.5
thick	34	66	390	246-283	3.1
thin	50	50	330	250-318	3.25
thin	66	34	385	245-296	3.45
thin	45	55	195	270-280	2.15
thin	41	59	215	270-300	2
thin	22	78	400	250-270	3
thin	21	79	440	250-270	3
thin	18	82	325	215-234	1
thin	10	90	395	210-220	1.1
thin	55	45	295	300-350	1

there is inconsistency in the results shown in italics due to wrong estimation of initial moisture content

Table -2 Solid Yield at Varying Torrefaction Temperature

Temperature, °C	Residence Time, hour	Solid yield, %
180-220	5.0 – 6.5	81 – 83
225-250	6.0 - 7.0	70 – 78
250-280	6.0	66 -72 (55 – 79)
280-300	4.0	55 -63 (50 – 66)
300-350	5.0 – 6.0	43 – 45

During torrefaction process decomposition reactions results in bamboo becoming completely dry and loose its tenacious structure. Also, the hygroscopic nature of the biomass is transformed to become hydrophobic. Besides this, the process increases the calorific value of the end product.

The challenging part of the development process was to identify a criterion for the completion of the torrefaction process. The extent to which the end product has become hydrophobic was found to be the only valid criteria. . Towards this the end product was subjected to humidity tests by exposing it (a) to atmosphere for prolonged duration of time (b) humidity above 95% for 24, 48 and 72 hours. The outcome of these studies is shown in Fig. 5 and 6. Under ambient conditions, the maximum absorption of moisture is less than 4% against nearly 10% in the case of raw bamboo. Similarly studies under humid conditions of over 95% indicate moisture absorption of about 6% against 11% with raw bamboo. These studies clearly emphasize achieving of hydrophobicity during torrefaction process.

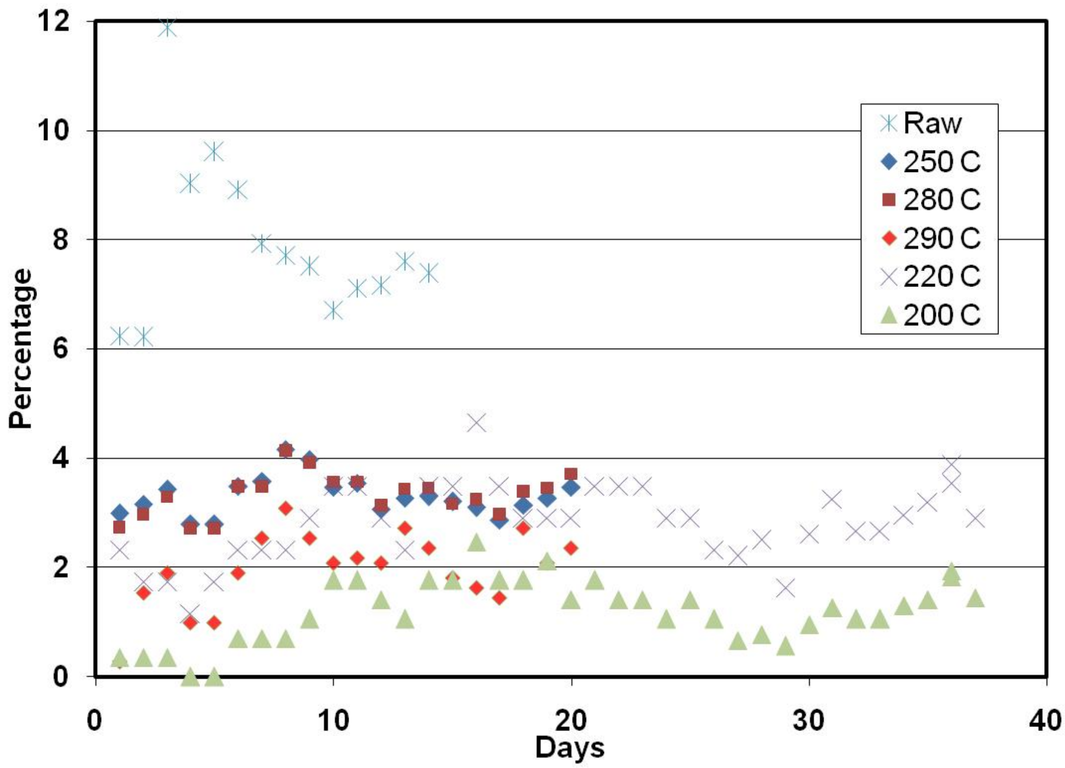


Fig. 5 Moisture absorption test: raw and torrefied bamboo exposed to ambient

Plate 6 shows the bamboo that was used for the experimentation. Plate 7 shows the process sequence to obtained grey charcoal from bamboo. Plate 8 shows the products obtained by subjecting the bamboo at varying temperatures.

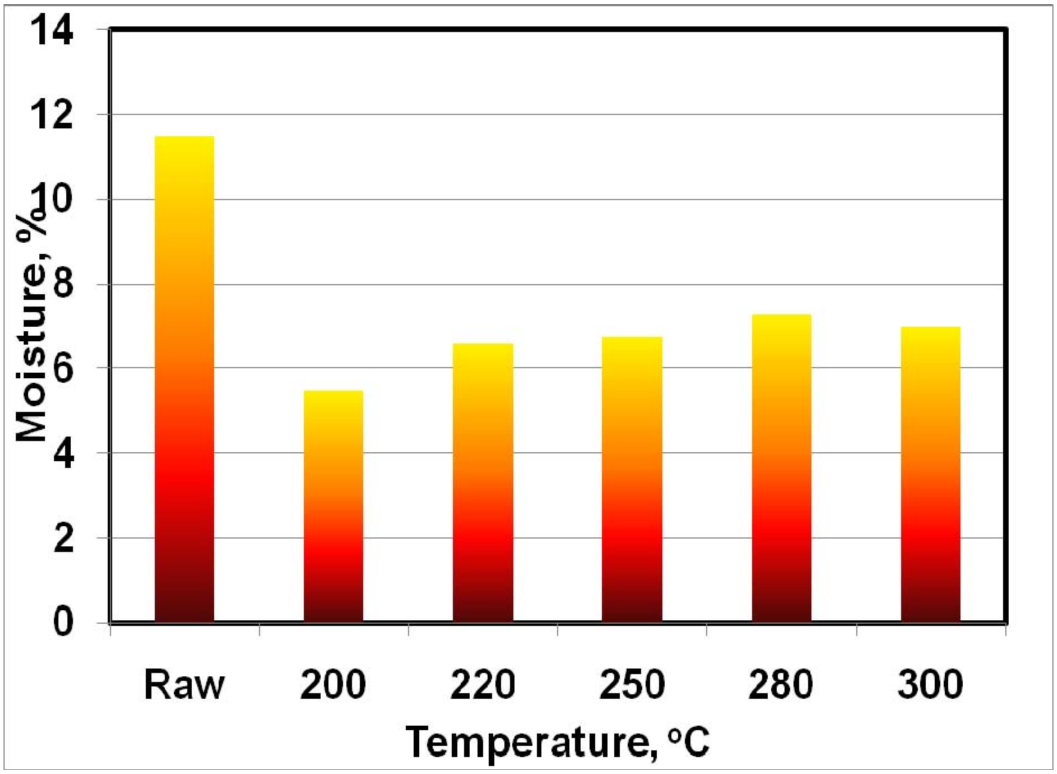


Fig. 6 Moisture absorption test: raw and torrefied bamboo exposed to humid environment (95-98% Relative Humidity)

Plate 6: Bamboo procured for the trails

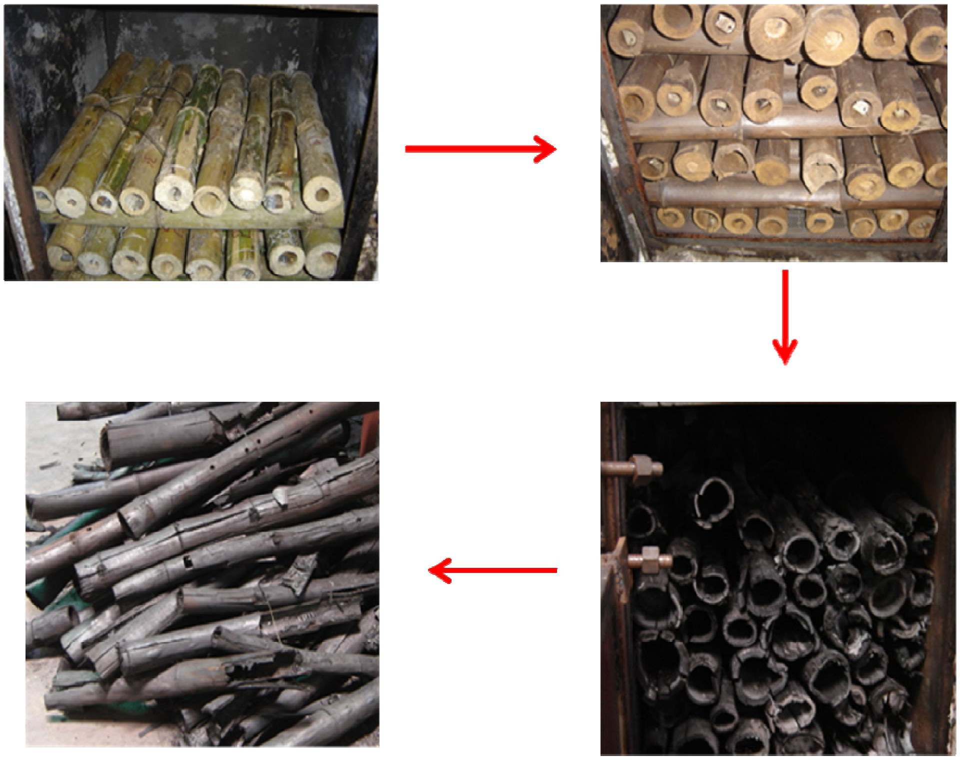
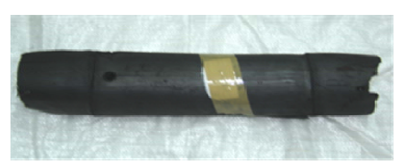


Plate 7: The Process Sequence

200° C

250° C

280° C



300° C

Plate 8: Torrefied Bamboo at Varying Temperatures

The Pilot Plant

Design & Description of Test Plant

The test plant of 50 kg/hr plant shown in Plate -9 & 10 was commissioned in May 2006. The test plant is an extension of the batch type lab scale system, wherein initial trials were conducted. The pilot plant is designed for continuous operation and meant for production of torrified bamboo. The test plant comprises of six identical chambers (each measuring 1 x 0.55 x 0.85 m) juxtaposed to each other with adequate thermal insulation. Each of the chambers has provision for hot flue gas entry at the bottom and exit at the top. The entry part of all the chambers are connected to one common manifold whose other end forms the exit of the combustion chamber. Similarly exit of all the chambers are connected to another common manifold whose other end is connected to a recirculation blower. There is isolation valves provided on the entry and exit side of each of the chambers. The details of test plant is schematically is shown in Fig. 7.

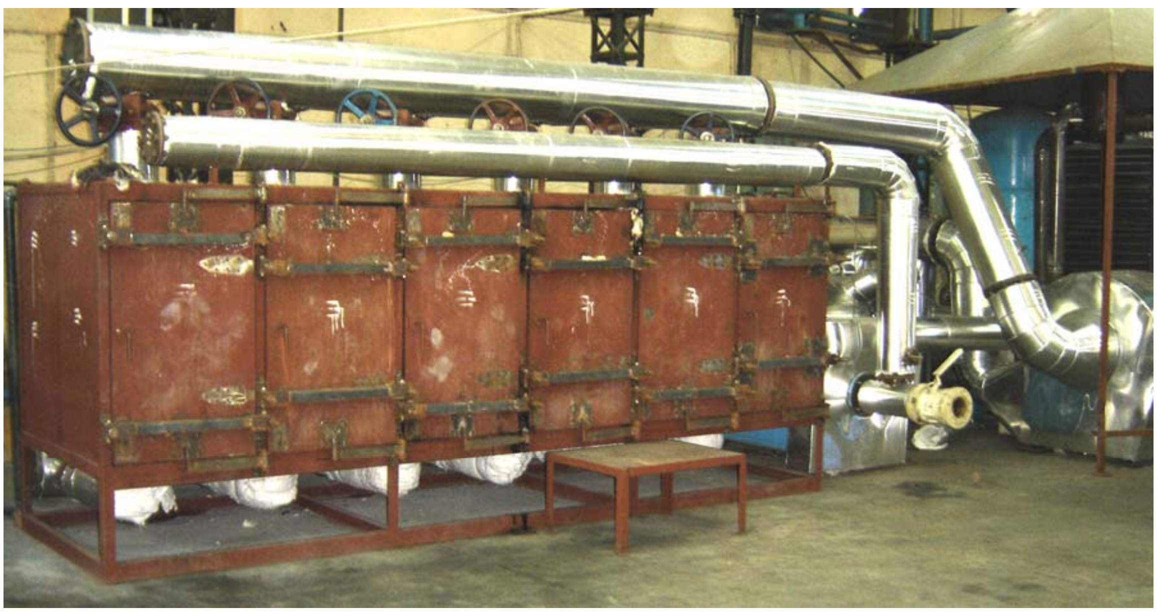


Plate 9: The 50 kg/hr pilot plant

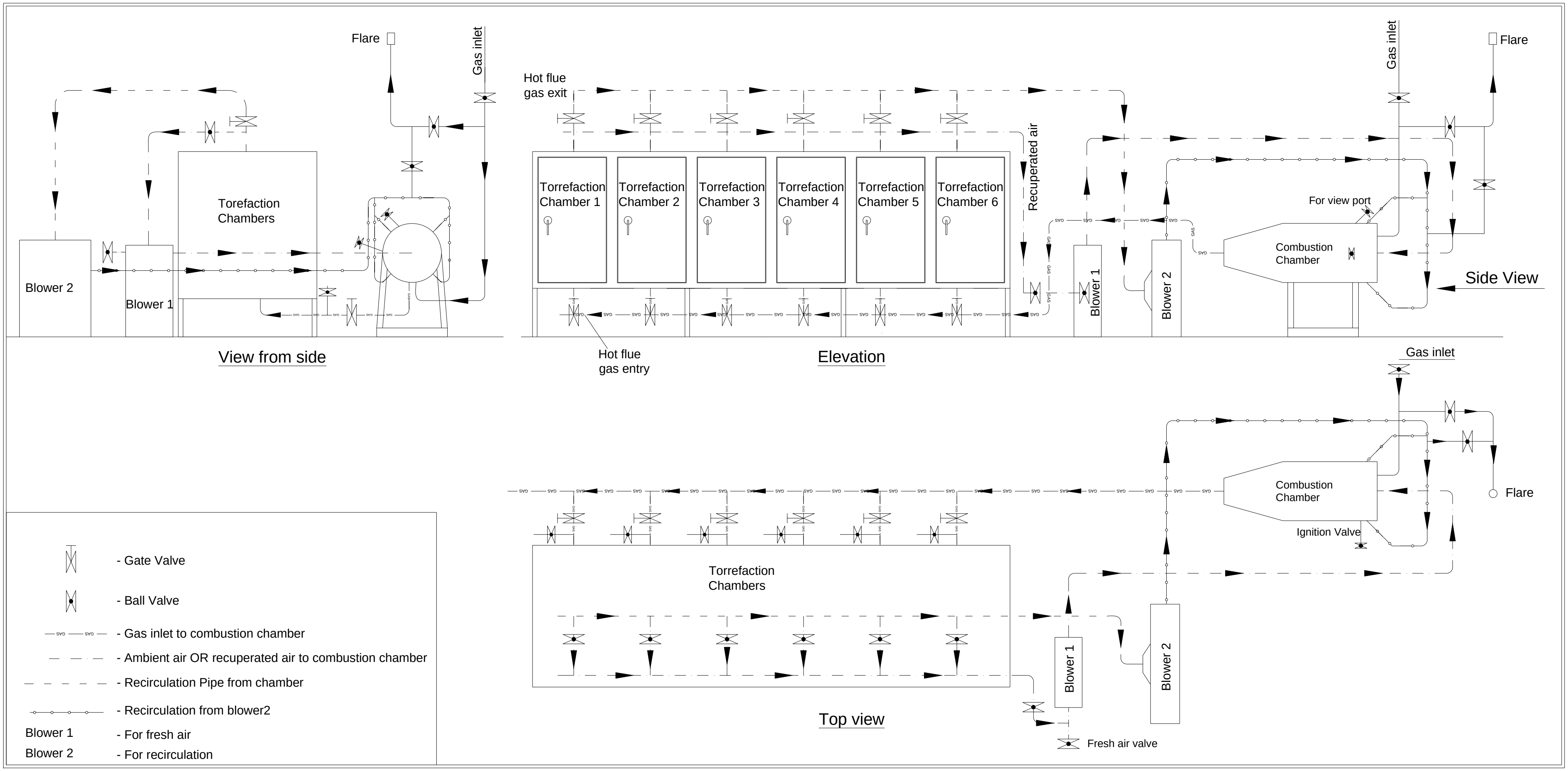


Fig 7 Schematic of the Pilot Plant

Plate 10: Thermocouple instrumentation on the Torrefcation Chambers

The heat source for torrefcation was obtained by combusting producer gas + air mixture in the combustor. The producer gas was generated in a gasifier system using waste wood as the feedstock. A 30 kg/hr capacity gasifier would suffice the requirement. The air for combustion was supplied by a separate blower, which had provision for supply of air either from the ambient or hot air (recuperated heat) sucked through the chambers undergoing cooling process. In order to achieve this, provision was made for fresh air entry to each of the chambers to facilitate heat recovery. The complete system including the blowers were insulated and cladded to reduce heat loss and improve the overall efficiency of the system. The connected electrical load of the two blowers was about 4 – 5kWe. Each of the torrefaction chambers was provided with thermocouple (see Plate 10) for temperature measurement and display. Similarly is the case with the combustion chamber. The temperature data was acquired on to a PC during lab trials and this would not be required for field trials since a temperature display is supplied along with the equipment. Also, the system is equipped to measure the gas flow rate, re-circulation rate etc.

Each of the chamber is designed for 0.47 m^3 (1 x 0.55 x 0.85 m) capacity and therefore can hold an input charge of about 70 kg of sun dried bamboo sticks (moisture ~ 10%) and 90 - 110 kg of raw bamboo (35 to 45% moisture). The plant is designed for 6-7 hours of heating and 4 hours of cooling time (estimated), which would complete one cycle. This works out to about handling of 50 kg/hr of raw bamboo and 35 kg/hr of sun-dried bamboo in a continuous mode of operation.

Operational Procedure

The system is designed for continuous operation, wherein one or more chambers are subjected to torrefcation process. The torrefcation process needs to be conducted under controlled heating rate conditions in order to achieve the best results. The optimum process time to reach a targeted temperature of 250° C is about 6 – 7 hours, followed by cooling to ambient condition. This optimum heating rate has been arrived on the basis of pilot scale studies conducted earlier. The required hot flue gas needs to be supplied from the combustion chamber, wherein it should be ensured that the oxygen content in the flue gas is maintained below 2 - 3% to prevent combustion of the charge or volatiles released during the process. The heating rate can be ensured by maintaining a certain temperature profile of the hot flue gas entering the chambers. This could be controlled by varying the amount of producer gas + air mixture combusted. Also, major part of the hot gases is recirculated to improve the overall efficiency of the process. Some part of the hot gas (equivalent of air + producer gas) needs to be let out to the ambient in order to permit operation of the combustion chamber. These gases invariably contain volatiles and therefore can't be allowed to escape unburnt leading to air pollution. The hot gas containing volatiles can't sustain combustion as it is fuel lean and therefore requires some support fuel. This can be achieved by burning a small quantity of producer gas (a separate stream taken out from the gasifier) as the support fuel (in a flare). The heat generated by this process could probably be used for drying of biomass that is fed as feedstock in the gasifier. In the current development this issue is not being addressed and the burnt products from the flare is being let out to the atmosphere.

After the completion of torrefcation process (after 6 – 7 hours of heating), the first set of chambers are isolated by closing appropriate valves and simultaneously the next set of chambers are initiated into the torrefcation process. So the combustion chamber supplies hot flue gases to the next set of chambers. Provision is made for heat recovery from the chambers that is undergoing cooling process; this is achieved by drawing cold air through hot bed of charge and the hot air supplied to the combustion chamber. This operation is expected to improve the overall efficiency of the process.

The Trials

Four trials were successfully conducted with the pilot plant at the laboratory. The first trial was essentially conducted in batch mode in order to understand and establish the operational procedure. There was an issue of air ingress into the torrefcation chamber that was subsequently rectified by using better quality gaskets. Similarly provision was made to combust some of the volatiles before they are let out to the ambient as mentioned earlier. One trial was conducted in a continuous mode for about 30 hours, wherein about 600 kg of raw bamboo was loaded in 22 hours.

The mode of operation was as follows: Three chambers were loaded with raw bamboo of 10% initial moisture content (about 70 kg per chamber) and subjected to gradual heating for about 7 hours to attain a temperature of 220° C. Later the flue gas supply was cut-off to these chambers and supplied to the remaining three chambers. The first three chambers were allowed to cool, but due to air ingress into the chamber the temperature increased to about 270 – 300° C in two of the chambers and therefore the cool off period was longer than anticipated. The cooling period stretched to 300 – 350 min against 240 min that was planned. In the manner the heating-cooling cycle of the chambers were continued for about 30 hours. The average torrefied bamboo yield was about 16 kg/hr (solid yield about 65 – 70%). In one of the subsequent trial, the cooling cycle could be completed within 240 min. The Plate - 11 shows the torrefied bamboo generated from the test plant.

Plate 11: Torrefied Bamboo from the Test Plant

A long duration trial of 76 hour duration was conducted wherein bamboo with 42% initial moisture was used. The heating time was about 7 hours and cooling time was reduced to about 4.5 hours. The cooling process was shortened by adapting a two step cooling strategy wherein initial cooling for about 3 hours was done by allowing the chambers to cool out naturally and once the temperature reached below 160 – 170 °C, cold air was sucked through the bed. This reduced the cooling time from 6 hours to about 4.5 hours.

Characterization of Grey Charcoal from Bamboo

The torrefied bamboo or grey charcoal was further characterized in terms of its composition and calorific value. Both proximate and ultimate analysis was conducted. Proximate analysis was conducted to determine the fraction of volatile and fixed carbon content. The results of the proximate analysis on moisture and ash free basis are shown in Fig. 7, wherein it is evident that increasing the temperature reduces the volatile fraction and increases the fixed carbon. The raw bamboo has about 85% volatiles and 10% fixed carbon is transformed to contain about 73% volatiles and 27% fixed carbon after subjecting to a torrefaction process at 250 – 275° C. The process when carried at 350 °C results in higher fixed carbon content up to 64%

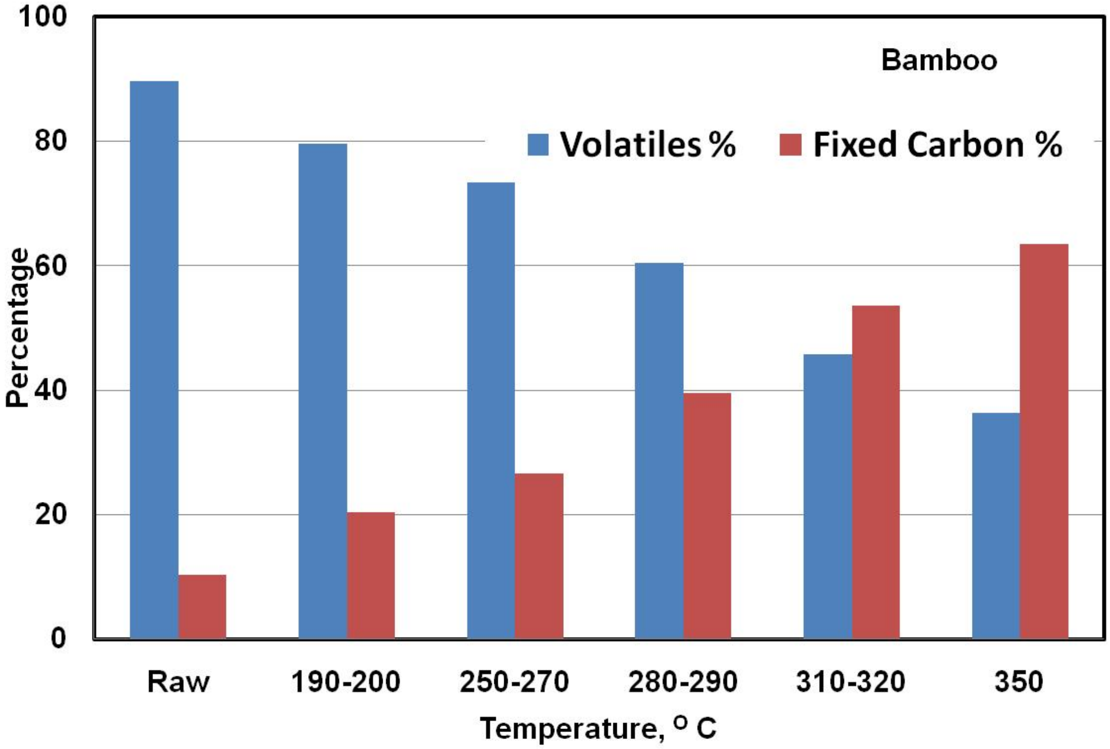


Fig. 7 Proximate Analysis (on ash and moisture free basis) of the Torrefied Bamboo at Varying Temperatures.

Further the samples were subjected to ultimate analysis where the elemental constituents like hydrogen, carbon, oxygen and ash were determined. Fig. 8 shows the elemental analysis wherein there is a reduction in oxygen element and correspondingly increase in the hydrogen and carbon content with the increase in temperature. Therefore torrefaction process results in reduction in O/C ratio, which essentially contributes to increase in the calorific value. The ash content in the raw bamboo is about 2.5% and increases to about 5.5% with grey charcoal at 350 °C.

A very important property is the increase in energy density of the torrefied bamboo compared to raw/untreated bamboo as shown in Fig. 9. The gross heating value of torrefied bamboo was found to increase with temperature: a 20% increase was observed at 250-260 °C (from 17.6 to 21.1 MJ/kg on dry basis). If the heating value of raw bamboo is corrected for the heat of evaporation of the moisture present, the actual increase brought out by torrefcation would be much higher.

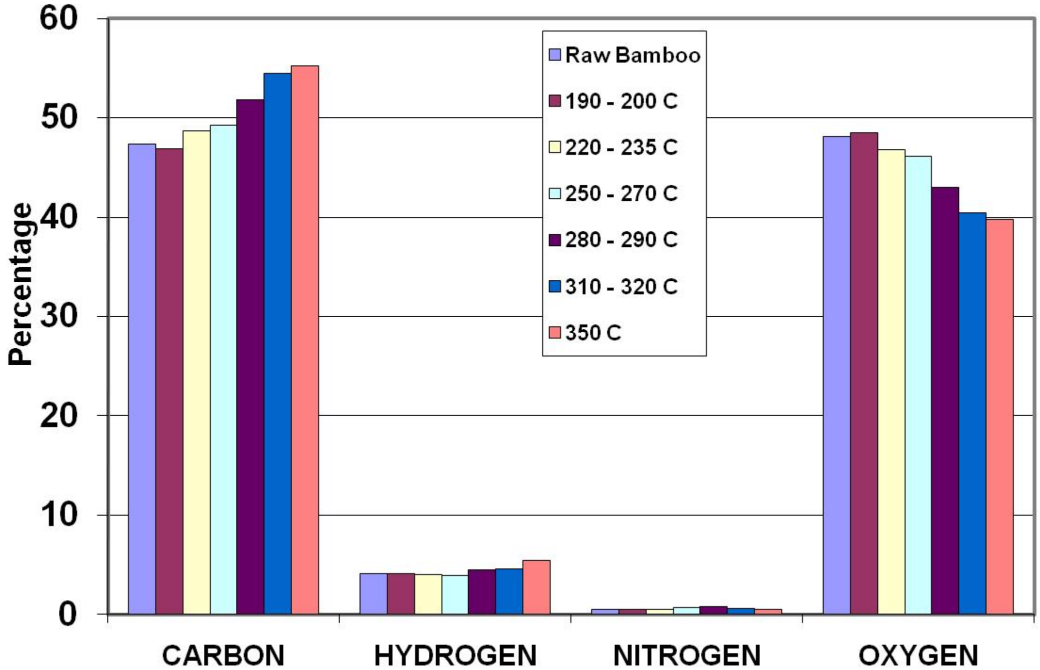


Fig. 8 Ultimate Analysis of Torrified Bamboo

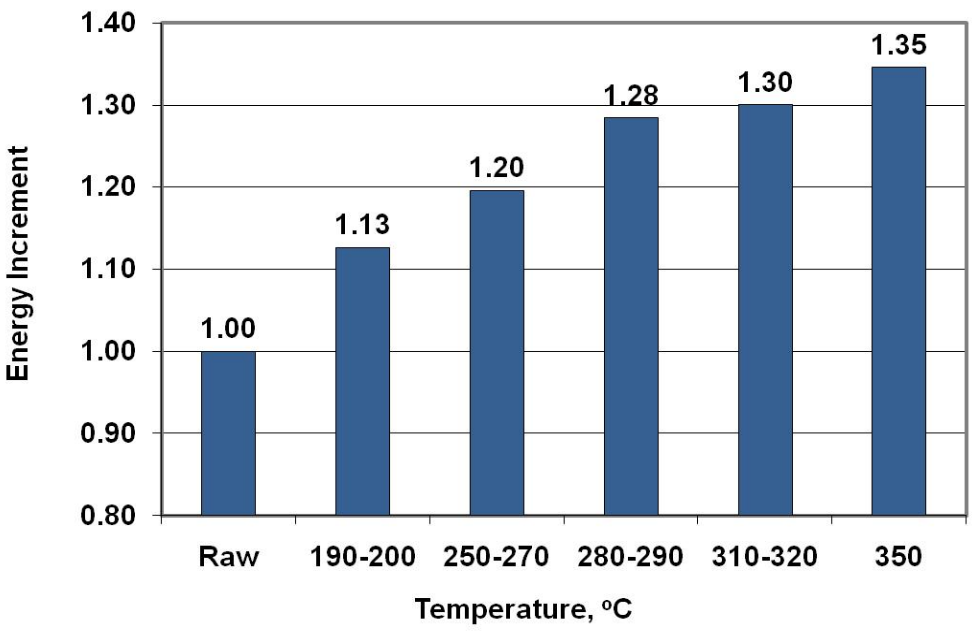


Fig. 8 Energy Density of the Torrefied Bamboo at Varying Temperatures. The reference measurement is the Gross Calorific Value of raw bamboo which is 17.6 MJ/kg on dry basis.

Techno-economics

Assumptions:

Cost of green bamboo: 250 Rs/ton
Biomass cost for Gasifier: 1000 Rs/ton
Electricity: Rs 3.50/kWh

Calculations:

Nature of Expense	kg/hr or kWh	kg or kWh in 24 hr	Cost, Rs
Raw bamboo	50 kg/hr	1000 kg	250
Fuel - biomass	25 kg/hr	600 kg	600
Electricity	6.75 kWh	162 kWh	567
Manpower	lump sum		700
Total cost			1867

Production cost for a production of 459 kg of torrefied bamboo	4.07/kg
Market rate for black charcoal	7 – 8/kg

Plant dimensions of higher throughput

Plant Dimensions for 10 Ton/day:

Bamboo to be processed	kg/day	10000
No. of batches/day		2
Batch capacity	kg/batch	5000
Density of bamboo	kg/m^3	450
Total Volume of chambers	m^3	12.7
Chambers	No.	6
Volume of each chamber	m^3	2.12
L x B x H	m	1.28
Capacity of each chamber	kg	952.5
Recirculation blower of 200 mm head	m3/hr	16000
Gasifier Rating	kg/hr	300

Plant Dimensions for 20 Ton/day:

Bamboo to be processed	kg/day	20000
No. of batches/day		2
Batch capacity	kg/batch	10000
Density of bamboo	kg/m^3	450.00
Total Volume of chambers	m^3	25.40
Chambers	No.	6
Volume of each chamber	m^3	4.23
L x B x H	m	1.62
Capacity of each chamber	kg	1905
Recirculation blower of 200 mm head	m3/hr	32000
Gasifier Rating	kg/hr	600

Conclusions

The following are the conclusions arrived at the completion of the project:

1. Torrefaction of bamboo has been successfully demonstrated and grey charcoal generated with an increment of calorific value by 20% corresponding to a torrefaction temperature of 250 °C.

2. Around 250 °C bamboo is found to have lost its tenacity and turning out brittle. So around 250 °C could be identified as the torrefaction temperature for that particular species bamboo.

3. The grey charcoal from bamboo is also found to have become hydrophobic, with maximum moisture absorption of about 6% against 12% with raw bamboo.

4. The pilot plant has been successfully tested and the designed throughput of 1 ton/day (based on input raw bamboo) has been achieved.

5. The pilot plant is being shifted to Nagaland Bamboo Development Agency (NBDA), Dimapur, Nagaland for field trials where this hardware would be integrated with the existing 135 kg/hr gasifier.