

## CONSTRUCTION OF A PACKED-BED PYROLYSIS REACTOR FOR CHARCOAL PRODUCTION

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**Abstract:** The paper pivoted on processing forest waste, Austrian Pine, for producing carbon enriched char. A small-packed bed reactor was developed to pyrolysis the processed char. The preparation of feedstock was carried out in an improvised muffle furnace. The following parameters were obtained to determine the potential of pine waste: thermal effectiveness, oil yield, char yield, gas yield, specific biomass consumption, and carbon conversion efficiency of the unit. The absolute increase in the cold gas efficiency of pine needles after torrefaction was 44%. As compared to Acacia wood chips (G30 and G50), a 4.8% rise in the carbon conversion efficiency was seen after thermal pre-treatment of pine needles. However, it was relatively dropped by 2% to the wood pellets. The obtained char yield from torrefied pine needles as to the wood pellets was augmented by 160%. On the contrary, the oil yield derived from torrefied pine pellet was dropped by 65% while comparing it with the wood pellets. The carbon dioxide emission was mitigated by 3.4% after torrefaction of raw pine needles, whereas it was reduced by 11.71% when it was compared with commercial wood pellets. A pronounced rise of 123% in the clean gas production was noticed after the torrefaction of pine needles, while it was 14.96% when it was compared with the wood pellets.

**Keywords:** packed bed, char, pine waste, thermal performance, wood pellets, clean gas

### 1. Introduction

Diversification of fuel sources has become a common practice for energy generation, but some waste materials are abundant in nature and could be exploited for the same. The majority of energy companies focuses on the standard fuel for domestic and international consumption, but it could be economically more viable and environmentally friendly if the waste loose biomass is also used. However, some designing complications are appended with them, but with the suitable processing technique, it could be utilised in different thermochemical processes.

According to the general policy framework of the EU, the share of renewable energy must be increased by 32%, an improvement of 32.5% in the energy efficiency of the system, and carbon emission must be abridged by 40% as compared to the base year 1990 [1]. For promoting bioenergy, another initiative was taken in Paris Climate Agreement by the EU that functioning of the coal-based power plant would be shunned by 2030 [2]. What are alternatives do we have to get clean energy? Either tap the solar energy or go for waste biomass management. In 2014, the parallel experiments were conducted on the 120 kW and 10 kW of the throat-less gasifiers to know the suitability of the loose biomass, pine needles, and it was found that the overall thermal efficiency of the system was 76.66% for 120 kW, whereas it was 76.5% for a small-scale unit. It was noticed that the loose biomass could be used in the different sizes of gasifiers with marginal change in its thermal performance [3, 4]. Similarly, a small unit for pyrolysis purpose was developed in the Institute of Agriculture Mechanisation. were thermally decomposed, and the thermal efficiency of 47–48% was obtained while carrying out the thermal decomposition of the Austrian standard wood chips, ONORM G30 and G50 (if the unit height is 320 mm) [5, 6]. Similarly, various technologies were used for the thermal decompose of woody biomass and it was noticed that thermal efficiency varied from 36.1% to 58.6% [7]. So, even state-of-art thermochemical transformation was not much promising for biomass conversion.

After reviewing the different types of technologies, it was noticed that the thermal effectiveness of the unit was not much influence despite using miscellaneous solid biomasses.

In this paper, a miniature of the pyrolysis reactor was constructed for thermally processed black pine needles pellets. The assessment of a unit was based on the cold gas efficiency (CGE), carbon conversion efficiency (CCE), apparent thermal efficiency, specific biomass consumption, and yield of char, gas and pyrolysis oil.

## 2. Materials and Methods

The pine waste was collected from Pest County of Hungary. The net 10 kg of pine needles were prepared and processed at the National Centre for Agriculture Research and Innovation, whereas the fabrication of a small-scale reactor was done at Edison Energetic Lab, Institute of Process Engineering, Szent Istvan University, Hungary.

### 2.1. Preparation and processing of loose biomass

For the milling purpose, a 1.5 kW rotor grinding machine (Retsch SM 2000) was used. The feed rate of the material was kept between 0.2 to 0.3 kg·h<sup>-1</sup>. A sieve of 1.5 mm was considered for filtering the milled material. The milled form of pine needles is shown in Fig. 1. After finishing the milling process, the moisture content of the end product was measured before the densification process.



Figure 1. The milled pine needles for the densification process

A 1–2% of water was added to the milled pine needles which were thereby heated to 70°C approximately. The heat is usually supplied to ensure that the lignin is released, and it would impart the binding ability to the particles.

For densification purposes, a ring-type pellet machine (CL3, Pellet mill) was used (Fig. 2). A screw extrusion of milled feedstock was carried out by feeding the material into a barrel via a hooper. The screw aims to push the material into the chamber where the roller presses the material against the ring die. The length and diameter were calculated to be 25.95 mm and 6.39 mm, respectively. It is worth mentioning that the gap between the die and roller impacts the quality of the pellets, wearing of the machine components and the energy consumption during the densification process.



Figure 2. The ring-type pellet machine

Around 20% of extra energy is required if the gap is increased by 1 mm. However, it also reduced the dust content by 30% in the final product. Another factor is the pressure required to form a pellet. The compacting process elevates the temperature of the input feedstock. A material that requires a higher pressure would

ultimately block the holes in the die and thus hamper the densification process. The densified form of pine needles is shown in Fig. 3.



Figure 3. The pellet form of pine needles

## 2.2. Modification of muffle furnace

The thermal pre-treatment was performed in an improvised furnace that is based on the principle of the Joule heating system. A digital furnace (Nabertherm GmbH) was programmed to suit the quasi-static condition. The furnace used during the experimental task is illustrated in Fig. 4.



Figure 4. The improvised furnace for the torrefaction process

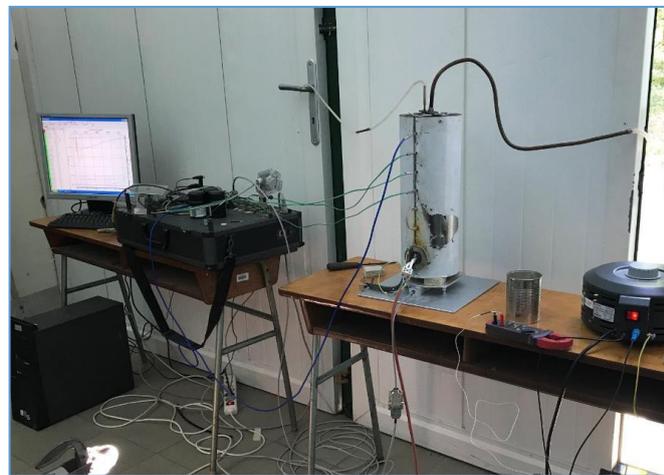
The nitrogen gas flowing at the volumetric rate of  $42 \text{ L} \cdot \text{min}^{-1}$  was used to inert the furnace chamber. The mass measurement was performed by connecting the mass holder to the weighing machine via a mechanical link. The lid ( $313.15 \text{ mm} \times 250 \text{ mm}$ ) for the furnace was modified to hold the pine pellets until the furnace attains a predetermined torrefaction temperature. For the flow of nitrogen, ducts of 21.5mm diameters were provided on the hollow cylinder and the rectangular frame of the lid. To cool down the system, a fan was bolted along the structure to inhibit the heating of protruded cylindrical section. The volumetric flow rate of the nitrogen was measured by the gas flow meter (Ganz 2000). Once the furnace attained the desired temperature, the sample was immediately fed into the chamber. The thermal profile for the torrefaction process was controlled by a digital console. The thermally processed material is shown in Fig. 3.7.



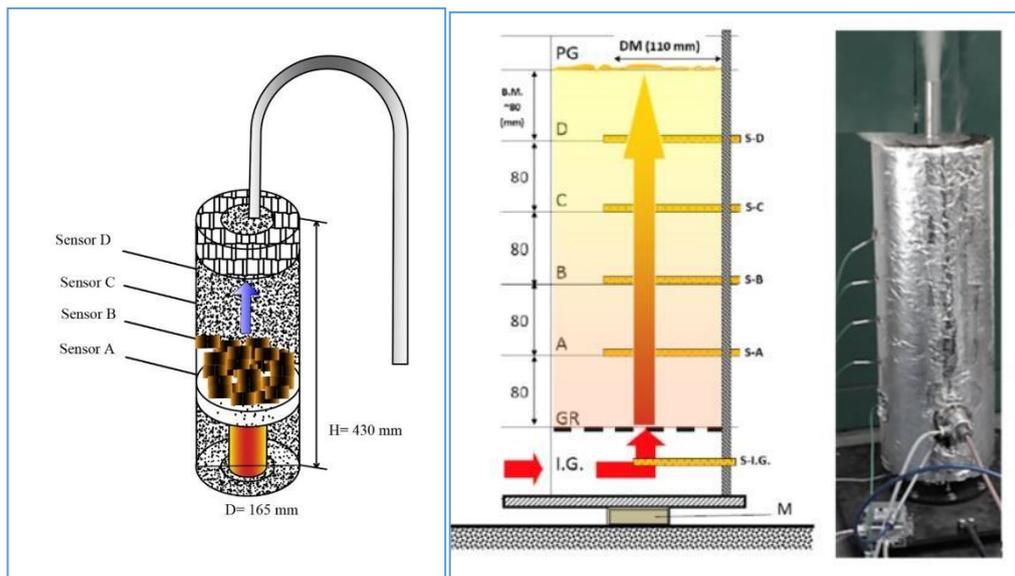
Figure 5. Thermally pre-treated pine pellets

### 2.3. Fabrication of the experimental rig

The preliminary drafting of the pyrolysis unit was carried out in AutoCAD (Autodesk, 2019). The inner shell of the reactor was fabricated from 1.45 mm thick welded carbon steel. The height of the reactor from the base is 430 mm, whereas the inner length was measured to be 400 mm. A clearance of 30 mm was provided between the inner and the outer shells. A 41.5 mm thick rock wool coating was provided to prevent heat across the outer shell of the reactor. The outer covering of the rock wool was done by a galvanised steel sheet. The diameter of the outer and inner shells of the reactor was 165 mm and 85.2 mm, respectively. For temperature measurement, the ports were produced along the length of the reactor. The distance between ports was kept at 43.8 mm. A small duct of 5mm diameter was provided for pressure measurement. A lid was also fabricated for providing additional heat insulation to the main body. The length and diameter of the lid were 71.6 mm and 118.4 mm, respectively. A grate of 79.55 mm in diameter was formed to carry the ash and char of feedstock. A concentric ceramic casing was provided for securely holding the heating element in the helical grooves engraved on the inner ceramic casing. The height of the heating unit was 153 mm from the bottom of the inner shell. The inner and outer diameter of the concentric casing was measured to be 47 mm and 73mm, respectively. To prevent the ingress of air, an airtight gasket was placed between the lid and flange provided at the bottom of the shell.



(a)



(b)

(c)

Figure 6. a: A small-scale pyrolysis unit; b: technical drawing of the proposed unit [8]; c: MGI pyrolysis unit (inert gas-based) [5, 6]

## 2.4. Metrology of the thermal system

The temperature measurement was performed by a 16-channel data acquisition unit (HBM). The thermogravimetric evaluation was carried by a strain gauge. The thermocouples type K (Ni-Cr) was used to measure the temperature at the designated ports. The producer gas measurement and its sampling were conducted by the Wood gas analyser (VISIT-03H, Messtechnik EHEIM GmbH). The sampling rate was preset at a volumetric rate of  $0.7 \text{ L} \cdot \text{min}^{-1}$ . The wood gas analyser involved in the measurement process is shown in Fig. 7. The gas wash bottles filled with refined oil and distilled water were used to trap the gaseous byproducts during pyrolysis reactions. Once the gas got cleaned, it went for further processing in the wool filter, activated carbon, and activated alumina soaked in potassium permanganate so that the dry producer gas could be obtained. The remaining condensate formed during the cleaning process was expelled through the water port provided on the console of the gas analyser. It is to be noted that before letting the gas be washed, a condensate trap was provided to remove the pyrolytic oil formed during the thermal decomposition of processed pine needles pellets. The dust and tar collection were performed at a sampling rate of  $0.6 \text{ L} \cdot \text{min}^{-1}$ . A 50 mL of isopropanol was used to dissolve the collected oil in the bottle placed in an ice bucket. Before beginning the sampling process, the volumetric suction rate of the pump was calibrated by a gas meter.



Figure 7. The wood gas analyser for the gas measurement



Figure 8. The single-stage rotary evaporator for distillation [8]

The filtration of pyrolysis oil was done at Regional Knowledge Center, Szent Istvan University. A 50 mL of isopropanol was used as a solvent to collect the oil, which was later distilled by a rotary evaporator (RVO 400, Boeco). The single-stage evaporator is shown in Fig. 8. The operating conditions used during distillation are provided in the literature [4]. To distil the isopropanol, the vacuum pressure and temperature of the water bath were kept at 0.137 bar and  $60^\circ\text{C}$ , respectively. The decanter was allowed to undergo 70 revolutions per minute until no further condensation of isopropanol was noticed. The mass of the mixture along with the decanter was measured before starting distillation.

## 2.5. Performance assessment of a reactor

To measure thermal as well as the energetic aspect of pre-treated pine pellets, the following parameters were calculated

### Carbon conversion efficiency (CCE)

The percentage of the total carbon converted to those components of producer gas that contain carbon is defined by CCE. The CCE can be given by Eq. 1. [9]

$$CCE \% = 12 \times V_g \times \frac{[CO\% + CH_4\% + CO_2\%]}{22.4 \times C\% \times W(1 - X_{ash})} \times 100 \quad (1)$$

In case the additional gas components  $C_2H_4$ ,  $C_2H_2$  and  $C_2H_6$  are also measured along with the producer gas, Eq. (1) can be written as

$$CCE \% = 12 \times V_g \times \frac{(CO\% + CH_4\% + CO_2\%) + 2(C_2H_4\% + C_2H_6\% + C_2H_2\%)}{22.4 \times C\% \times W(1 - X_{ash})} \times 100 \quad (2)$$

where CO, CH<sub>4</sub>, CO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> are measured on a vol% basis, whereas C% is the carbon fraction in the feedstock.  $W$  is the biomass feeding rate (g·h<sup>-1</sup>),  $V_g$  (Nm<sup>3</sup>·h<sup>-1</sup>) and  $X$  are the volumetric flow rate of producer gas and the ash content in biomass, respectively.

#### Steam decomposition (SD)

Decomposition of steam during thermochemical transformation can be given by Eq. (3) [9]

$$SD\% = V_g \times \frac{((H_2 + 2 \times CH_4) + 2 \times C_2H_4) \times \frac{18}{22.4}}{W_1 + W_2} \times 100 \quad (3)$$

Here,  $W_1$  and  $W_2$  are the steam flow rate and the moisture content in feedstock, respectively.

#### Apparent thermal efficiency (ATE)

Correspond to the oxidation of the feedstock, the energy conversion was presented in the context of apparent thermal efficiency. However, this factor is based on the effect of reactor temperature on energy yield. The producer gas to solid fuel energy ratio is defined as, [10]

$$ATE = \frac{Y \times HHV_g}{W \times HHV_b} \quad (4)$$

where  $Y$  and  $W$  denoted the gas yield and mass of solid biomass

#### Gas yield (Y)

The nitrogen content of the feedstock is relatively low therefore it was excluded while computing the gas yield. The dry gas yield,  $Y$ , based on ash-free biomass can be given by Eq. 5. [11].

$$Y = \frac{V_g \times 0.79}{W \times (1 - X_{ash}) \times N_2} \text{ Nm}^3 \cdot \text{kg}^{-1} \quad (5)$$

Here,  $N_2$  volumetric percentage of nitrogen in the producer gas.

#### Higher heating value (HHV<sub>g</sub>)

The heating value of the producer gas was measured with the help of a volumetric percentage of H<sub>2</sub>, CO and CH<sub>4</sub>. The higher heating value of gas can be derived from Eq. 6. [11]

$$HHV_g = 0.0418 \times (3.018 \times CO\% + 3.052 \times H_2\% + 9.5 \times CH_4\%) \text{ MJ} \cdot \text{Nm}^{-3} \quad (6)$$

#### Cold gas efficiency (CGE)

The cold gas efficiency of the reactor can be defined as the ratio of chemical energy of the producer gas to that of feedstock. Mathematically, it can be written as [11]

$$\eta_c = \frac{Y \times HHV_g}{HHV_b} \quad (7)$$

## 2.6. Physicochemical properties of raw and torrefied pine needles

The physical and chemical analyses of pine needles were conducted into two phases: Ultimate and proximate and Calorimetry. The ash measurement of the torrefied material was determined according to the NREL method [12]. The following equation was used to estimate the fixed carbon in the raw and thermally pre-treated samples. The material tested in the proposed pyrolysis unit was pre-treated at 250°C for 5 minutes.

$$F.C\% = 100 - \text{Ash}\% - M\% - V.M\% \quad (8)$$

The ultimate analysis of the samples was performed using a CHNS analyser (Vario MACRO elemental). The detailed analysis information is provided in the literature [8]. Information about physical and proximate analysis and the chemical composition of raw/ processed pine needles, hog fuel, wood chip and Mengxi coal are tabulated in Table 1 and Table 2, respectively.

Table 1. Variation in physical properties and proximate analysis of material upon thermal pre-treatment

Material	$\rho_b$ (kg·m <sup>-3</sup> )	HHV (MJ·kg <sup>-1</sup> )	Ash%	*F.C %	**V.M%
Raw	179.20	22.32	2.92	7.16%	89.92
Densified [13]	788	22.32	2.92	7.16%	89.92
Torrefied (250°C, 5 min.)	720.64	23.45	2.07	73%	21.48

\*Fixed carbon \*\* Volatile matter

Table 2. Chemical composition of different biomasses and coal

Material	C%	H%	N%	S%	O%
Raw	50.91	7.02	1.01	0.11	41.43
Torrefied	53.40	6.54	0.68	0.09	40.53
Wood pellet (Hog fuel) [15]	49.35	5.23	0.10	0.06	41.95
Wood chip (Acacia) [5]	50.03	5.84	0.07	0.06	42.94
Mengxi Coal [14]	87.50	6.50	1.00	1.50	3.50

### 3. Results and discussion

#### 3.1. Thermal performance of the reactor

A comparative assessment has been conducted based on the thermal potential of different biomasses that were tested in different kinds of reactors (Table 3). A non-inert powered reactor was compared with a microwave-based pyrolysis unit [14] and the MGI reactor [5]. It was found that the cold gas efficiency of pre-treated pine needles pellets was 31% lower than that of the wood pellets (hog fuel), whereas the carbon conversion efficiency of torrefied pine needles was found to be 4.8% higher than the wood chips, but 70.23% lower than that of raw pine needles. The absolute increase in the gas yield of raw pine needles after torrefaction was 83%, whereas it was 17.47% lower than that of the wood pellets. The char production ability of densified- pre-treated pine needles was increased by 689.47%. The derived char yield was found to be 122.71% higher than the wood pellets, but it was 25.90% lower than the char yield derived from microwave pyrolysis of coal [14]. The steam decomposition (SD) percentage during pyrolysis was calculated to 47.14% for torrefied pine needles pellets, which was 13.48% and 1745.51% higher than wood chips and wood pellets, respectively. The relative energy conversion was assessed with the help of apparent thermal efficiency (ATE). The apparent thermal efficiency of torrefied pine needles was computed to be 30% lower than that of the wood pellets, whereas the absolute percentage rise in ATE was 182% after the thermal pre-treatment of pine needles. The oil yield derived after torrefaction was noticed to be reduced by 65% while comparing it with the wood pellets. Similarly, the conventional pyrolysis of coal provided 94% less oil yield than the thermally processed pine needles. The heating value of the producer gas derived after thermal decomposition of the torrefied pine pellets was 1.57%, 142%, 99%, and 72.95% higher than that of wood pellets, wood chips, coal and the raw pine needles, respectively.

Table 3. Performance parameters for different types of biomasses and coal

Parameters	Processed pine needles	Wood chips	Wood pellets	Coal [14]	Raw pine needles
ATE	1.93	0.0038	2.76	0.0045	0.11
CGE %	44.53	0.18	64.38	0.20	0.63
Y (Nm <sup>3</sup> ·kg <sup>-1</sup> )	0.85	0.0065	1.03	0.0066	0.02
CCE %	13.66	13.03	13.94	0.96	45.89
Char yield %	60	26.94	23	80.98	7.6%
Oil yield %	10.48	-	30	0.62	-
HHV <sub>g</sub> (MJ·Nm <sup>-3</sup> )	12.28	5.06	12.09	6.17	7.1
W (kg·h <sup>-1</sup> )	0.23	0.47	0.24	0.44 [9]	0.055
SD%	47.14	41.54	17.11	2.02	10.75
V <sub>g</sub> (Nm <sup>3</sup> ·h <sup>-1</sup> )	0.036	0.2	0.036	0.006	0.036
Medium	-	Nitrogen	-	-	-

It was noticed that the thermal pre-treatment alongside densification of pine needles improved thermal efficiency, carbon conversion ability, char yield and quantitative aspect of the proposed design; however, it is still relatively lag behind the commercial hog fuel in the context of carbon conversion and cold gas efficiency. But the overall objective of charcoal production was drastically higher than the commercially available biomasses (G30, G50 and the wood pellets). Moreover, the fuel consumption rate ( $W$ ) was noticed to 4.34% higher than that of thermally processed pine needles, where it was increased to 104.34% when it was compared with the Acacia wood chips (G30 and G50). Similarly, coal pyrolysis consumes 91% more fuels than that of the proposed design. However, the raw pine needles require 76% less fuel to generate gas, but the overall charcoal production from the unit was exceptionally low, therefore the proposed packed-bed reactor was found to be not suitable for loose biomass. The solid material can generate up to 60% or more charcoal without any significant interrupt during the functioning of the small-scale reactor. The minimum ingestion period of the reactor was 3.60 min for processed pine needles, whereas it is around 12 minutes, so the overall delay of 8.4 minutes was seen during thermal decomposition of commercial biomass. The reason for higher carbon conversion efficiency is the relatively low thermal immunity of commercial pellets as compared to the torrefied pine pellets. The cold gas efficiency of processed pine pellet was attributed to the reduction in the dry gas yield obtained from the processed pine pellets. It could be controlled by adding a suitable catalyst to increase the hydrogenation of carbon monoxide and carbon dioxide and thus the overall clean gas production would also be influenced. Albeit the overall clean gas production after torrefaction was amplified by 14.96%. Another means of improvement is the water-gas shift reaction or expelling out nitrogen from the system via the Haber-Bosch process.

### 3.2. Thermogravimetry / Evolved gas analysis

The change in the extensive and intensive properties of the reactor with time are shown in Fig. 8 and Fig. 9, respectively. The initial mass of 0.3 kg had undergone thermal decomposition. The mass plateau was decreased by 56% during dehydration of the torrefied pine needles pellets when it was compared with the wood chips [5]. The ripples were noticed at the beginning of the pyrolysis. The reason for this effect was either owing to a sudden change in the heating rate of the system or evolving intermediate compounds. Since the applied voltage and power supply was kept constant, a thermal lag was seen during the pyrolysis of processed pine pellets. It indicated that thermal immunity of pre-treated biomass at a reduced temperature range was improved due to the cross-linking reactions. The surfacer adsorption was observed while carrying out the thermal decomposition of processed pine pellets and consequently, the system temperature was dropped by 15°C at the onset of the char formation stage. The dynamic pressure of the system was decreased from 0.6 Pa to 0 Pa during surface adsorption. It could be concluded from the thermogravimetric (TG) curve that surface defects formed during thermal pre-treatment have changed the TG behaviour of the processed pine pellets.

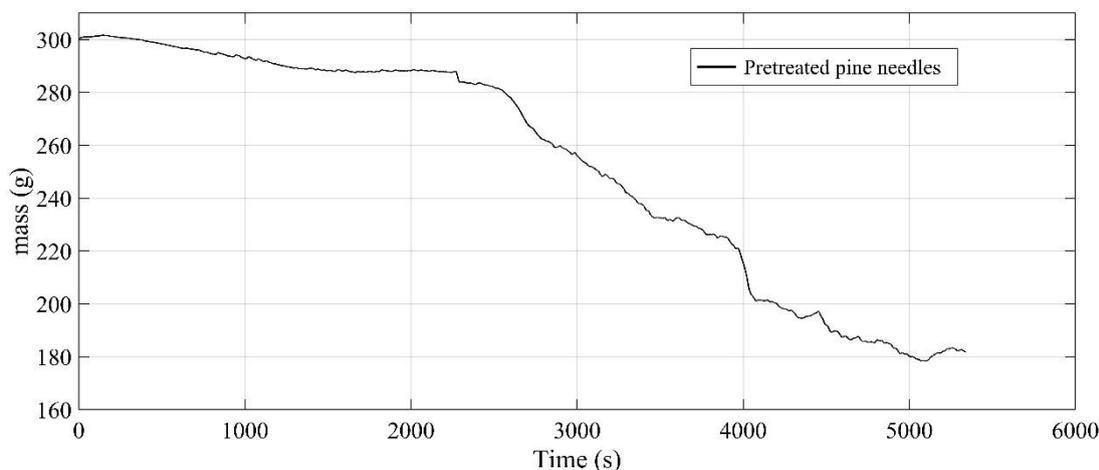


Figure 8. Thermogravimetric variation in pre-treatment pine needles with time

Besides thermogravimetric variation in the processed pellet mass, the intensive properties (Fig. 9) were also monitored. At the constant power supply, a steep rise in the lower bed temperature ( $A$ ) was observed at the onset of the pyrolysis process. The corresponding heating rate calculated during the thermal event was 3.89

$^{\circ}\text{C}\cdot\text{min}^{-1}$ . The sigmoidal nature in the thermal profile shows the simultaneous dissipation of heat and pressure taking place within the system. Once the lower bed (A) approached the cut-off point, the upper bed temperature tried to maintain the thermal equilibrium with the lower bed. A 24.26% rise in heating rate was seen during the desorption of moisture. The drying of processed pine pellets brought a significant rise of 76% in pressure that showed that eventually drifted away from the system from its thermal equilibrium. This was happened due to a rise in the partial vapour pressure of water content in the cellulose structure. The structural rapture of pine needles during the torrefaction increased the pressure-driven flow of fluid across the reactor and thus reduced the residence time of volatile in the reactor. The evolution of volatile during thermal decomposition of the processed pine pellets was seen in a temperature interval of 406–577 $^{\circ}\text{C}$ . The formation of the process was observed at 577–690  $^{\circ}\text{C}$ . The pressure drops while the formation of char was 212 Pa.

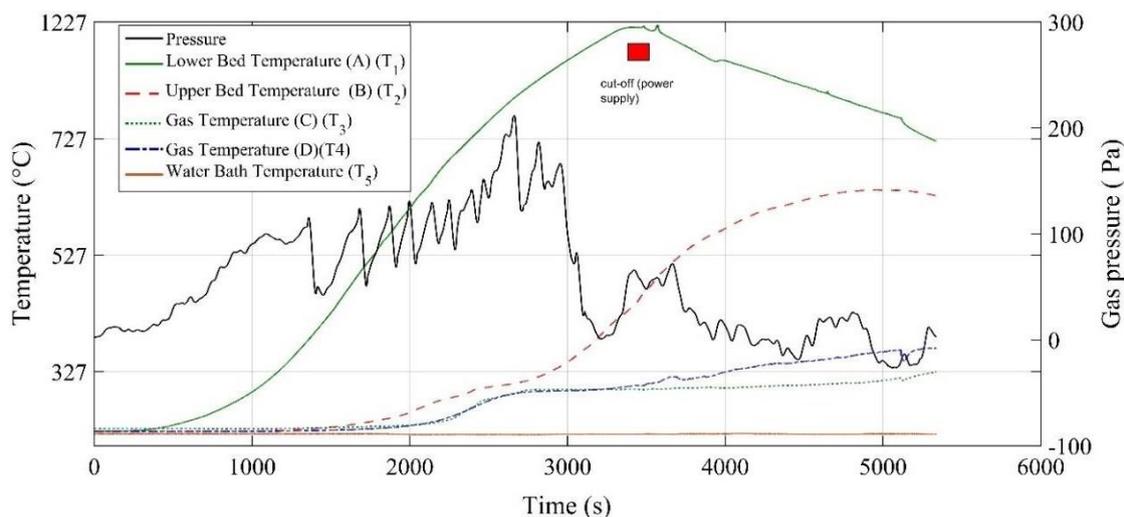


Figure 9. The change in the intensive properties of the system with time

The deviation in producer gas composition derived from processed pine pellets is illustrated in Fig. 10. The average gas composition derived during pyrolysis of the processed pine needle pellets, coal, raw pine needles, wood chips and wood pellets is shown in Table 4. It was seen that the emission of  $\text{CO}_2$  and  $\text{CO}$  fraction was decreased by 8.2% and 12%, respectively. Similarly, the rise in hydrogen and methane gases composition was 91.2% and 11%, respectively, when it was compared with wood chips [5]. It was observed that the release of volatiles was very abrupt as time proceeds. It happened due to water-gas shift reaction that eventually bolstered the percentage of hydrogen gas percentage in the producer gas. Once the hydrogen began to increase, the carbon dioxide and methane were got saturated with time.

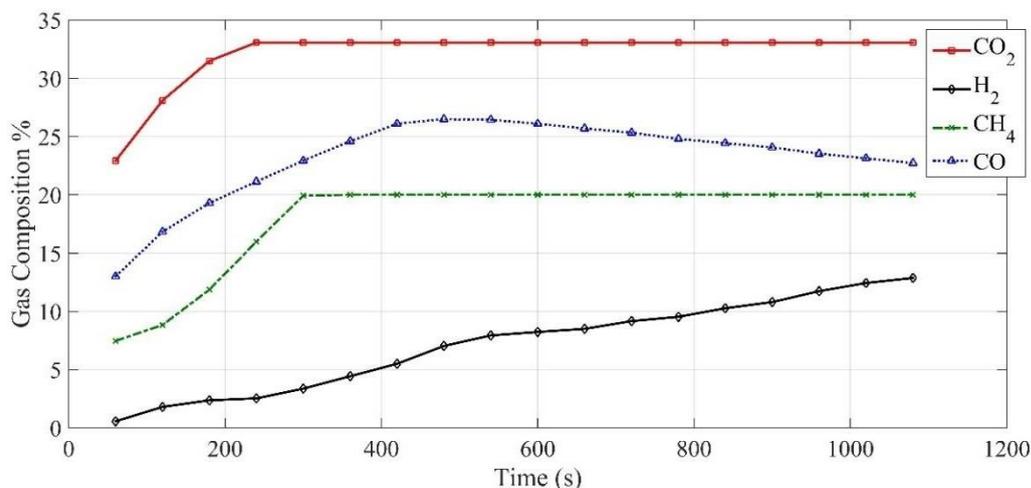


Fig.

Figure 10. The fluctuation in the producer gas composition with time

As compared to raw pine needles, coal, the wood pellets, the carbon dioxide emission was, respectively, seen to be reduced by 3.43%; 50.59% and 11.71%. The clean gas generation increased by 123.40% after the

torrefaction of raw pine needles, which was correspondingly 45.16 %, 14.96% and 200% higher than wood chips [5], wood pellets and Coal [14]. The operating medium also influences the gas composition as it was seen that the gas composition derived from wood chips had 250% higher nitrogen content in the producer gas than that of the processed pine needles pellets, whereas it was noticed to be the least during coal pyrolysis [14]. The influence of the medium affects the thermal performance of the reactor; therefore, it should be minimised during thermal decomposition.

Table 4. Gas composition derived from thermal decomposition of different biomass (vol%)

Material	CO%	CO <sub>2</sub> %	H <sub>2</sub> %	CH <sub>4</sub> %	N <sub>2</sub> %
Processed Pine Needles	22.80	30.90	11.50	20	14.80
Raw pine needles	24.50	32	5.90	8.20	29.40
Wood Chips [5] (Nitrogen reactor)	14.3	12.2	19.9	1.8	51.8
Wood pellets	25.40	35	7.40	20	12.20
Coal [14] (conventional pyrolysis)	23.07	62.54	3.35	7.14	2.02

#### 4. Conclusion

The following noteworthy points were derived during analysis:

- The proposed reactor was able to assimilate properly the solid biomass, but it had shown anomaly with loose biomass.
- The carbon conversion efficiency of the raw pine needles was decreased by 70.23% after torrefaction. The reason is thermal immunity is imparted due to cross-linking reactions.
- The fuel consumption of the processed pine pellets was reduced by 4.166% when it was compared with the commercial wood pellets.
- The gas derived from processed pine needles pellets was 5.96% and 14.96% cleaner than the wood chips and the wood pellets, respectively.
- The carbon dioxide emission was curtailed by 3.43% after the torrefaction of the raw pine needles, whereas it was further decreased as compared to coal and woody biomasses.
- The dry gas yield of processed pine pellets to the wood pellets was dropped by 17.45%. The reason is the excessive formation of nitrogen gas during the thermal decomposition of processed pine needles. It could be curtailed if the methanation and water-gas shift reactions are promoted via catalytic pyrolysis.
- The adsorption of gas accompanied a drastic drop in the pressure of the system.
- A sudden rise in hydrogen gas formation was owing to the exothermic reaction between water vapour and carbon monoxide.
- The steam decomposition was found to be maximum in the torrefied pine needles pellets among other biomasses and coal.
- The following reactor can be further modified if nitrogen is transformed into ammonia and thus the overall producer gas yield can be improved.

#### Acknowledgment

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