Biomass torrefaction: A promising pretreatment technology for biomass utilization

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Abstract: Torrefaction is an emerging technology also called mild pyrolysis, which has been explored for the pretreatment of biomass to make the biomass more favorable for further utilization. Dry torrefaction (DT) is a pretreatment of biomass in the absence of oxygen under atmospheric pressure and in a temperature range of 200-300 degrees C, while wet torrefaction (WT) is a method in hydrothermal or hot and high pressure water at the temperatures within 180-260 degrees C. Torrefied biomass is hydrophobic, with lower moisture contents, increased energy density and higher heating value, which are more comparable to the characteristics of coal. With the improvement in the properties, torrefied biomass mainly has three potential applications: combustion or co-firing, pelletization and gasification. Generally, the torrefaction technology can accelerate the development of biomass utilization technology and finally realize the maximum applications of biomass energy.

1. Introduction
As sustainable energy resource, biomass has recently attracted more interest from both political and scientific perspectives all over the world [1-3]. However, these biomass energy resources need special attention and more expensive solutions in terms of storage, handling, milling, and feeding compared to the existing system used for coal. There are some disadvantages of raw biomass listed in table 1, such as high moisture content, low bulk and energy density, poor grindability and hygroscopic nature [4-6]. These disadvantages embarrass the energy utilization of biomass.

| Biomass characteristics | Main challenges |
|-------------------------|----------------|
| High moisture content   | Reduce the heating value |
|                        | Require energy intensive drying step |
|                        | Reduce the efficiency of the conversion processes |
|                        | Increase storage and transportation costs |
|                        | Increase risks of biological degradation |
|                        | Increase corrosion because of condensation of water in flue gas |
| Low bulk and energy density | Increase storage and transportation costs |
| Poor grindability       | Require high feeding capacity |
|                        | Increase grinding energy |
|                        | More coarse particles |

Table 1. Disadvantages of raw biomass
Hygroscopic nature | Absorb moisture during storage  
High oxygen content | Reduce the number of high energy C-H bonds  
High alkali metal content | Make ash-related problems more serious  
Heterogeneity | Wide variation in properties

So far, biomass is turned into energy mainly in thermal process, including co-firing with coal for electricity, pyrolysis for bio-char, bio-oil and bio-gas or pelletization for pellet fuel which can be fit together with gasification process for gas fuel [7, 8]. But for the disadvantages listed in table 1, raw biomass must be pretreated for further utilization.

Torrefaction is a thermochemical treatment process that involves heating biomass at temperatures of 200–300°C in the absence of oxygen, during which the biomass partly decomposes, releasing different types of volatiles [9]. The final product of the process is the remaining solid, which is referred to as torrefied biomass if it is produced from woody biomass. Considerable energy densification can be achieved by torrefaction, as the remaining solid typically contains up to 90% of the initial energy content in only 70% of the initial weight of the biomass feedstock [10, 11]. A brief summary of gas, liquid and solid products from torrefaction are given in Table 2, and the properties of torrefied biomass will be discussed in detail in the following chapter.

| Classification | Light | Mild | Severe |
|----------------|-------|------|--------|
| Temperature(°C)| 200-235 | 235-275 | 275-300 |
| Consumption Hemicellulose | Mild | Mild to severe | Severe |
| Cellulose | Slight | Slight to mild | Mild to severe |
| Lignin | Slight | Slight | Slight |
| Liquid color | Brown | Brown dark | Black |
| Product Gas | H₂, CO, CO₂, CH₄, toluene, benzene and C₅H₆ |
| Liquid | H₂O, acetic acids, alcohols, aldehydes and ketones |
| Solid | Char and ash |

This paper reviews mainly on torrefaction technology, including the specific designing parameters of the process, the characteristics changes of solid product and the applications of the technology, and in this way promoting the full use of biomass energy and facilitating the generalization of torrefaction.

2. The main technology of biomass Torrefaction
Dry torrefaction (DT) or conventional torrefaction is a thermal pretreatment of biomass in the temperature range of 200–300°C. It is normally carried out in inert gas environment, under atmospheric pressure and with low heating rates (less or about 50 °C/min) [12]. The holding time at the maximum temperature can be various but generally less than 1h. Three kinds of products are produced after torrefaction: a solid product called bio-char, which contains about 90% of the energy in the remain 70% of the mass; a condensable mixture containing mostly water, organic components and lipids; permanent gases including hydrogen, carbon dioxide, carbon monoxide and hydro carbons such as methane. There are some factors that would have an effect on the torrefaction process, such as the torrefaction temperature, residence time [13], atmosphere [14] and biomass species [15].

In DT, three main drawbacks should be put forward to the public. Listed as following: (1) DT requires the feedstock being completely dried prior to the process [16, 17], thus reducing
the overall efficiency and increasing the operating costs of DT plants.

(2) The high ash content of bio-char restricts its utilization.

(3) The higher volatile matter and lower moisture content in bio-char may potentially increase the risk of self-ignition, causing fire/explosion, especially when integrating with densification that required higher force for bio-char than raw biomass.

Wet torrefaction (WT) is another thermochemical conversion process, also referred to as hydrothermal carbonization (HTC) or hydrothermal torrefaction (HT), on which lignocellulosic biomass with high moisture content treated in a subcritical pressurized water vessel from 1 to 250 MPa at 180–265°C in an inert environment for a residence time of 5 min to several hours [18]. Hydro-char is the main product of WT, which accounts for up to 88.3% of the mass and 89.1% of the energy in the raw biomass. The factors that would affect the torrefaction process are mainly the torrefaction temperature, residence time, pressure, atmosphere and liquid medium [19, 20]. In comparison, the grindability (including particle size and bulk density), hydrophobicity, and thermal stability of torrefied bamboo are considerably lower than that of bamboo hydro-char produced at the same temperature. Generally, the wet torrefaction process produces a solid with greater energy density than dry torrefaction, with the same mass yield [21].

The major differences and general properties of dry and wet torrefaction are listed in Table 3. In the process parameters, different temperature, pressure and reaction medium (including gas and liquid) lead to different residence time. DT process needs pre-drying while WT needs the drying process after the torrefaction is done. After the torrefaction process, many disadvantages discussed above are improved and turned into more favorable properties when swift to WT from DT, including lower ash content, high carbon content, higher energy density and heating value, higher hydrophobicity, improved fouling behaviors and so on.

Table 3. Summary of the major differences and general properties of dry and wet torrefaction

| Process | Dry torrefaction | Wet torrefaction |
|---------|-----------------|------------------|
| Temperature | 200-300 | 180-265 |
| Residence time | Less than 1 hour | 5 min to several hours |
| Pressure | Air | 1 to 250 MPa |
| Atmosphere | Inert | Inert |
| Liquid medium | None | Water/Steam |
| Pre-drying | Yes | No |
| Post drying | No | Yes |
| Toxic | A bit | Non-toxic |
| Product | Product | Gas, Tar, Solid | Solid, Gas, Liquid |
| Main product | Bio-char | Hydro-char |
| Ash content | Higher | Lower |
| Carbon content | Lower | Higher |
| O/C and H/C | Decreased | Decreased |
| Moisture content | Lower | Higher |
| Energy density | Lower | Higher |
| Heating value | Lower | Higher |
| Bulk density | Low | Low |
| Hydrophobicity | Lower | Higher |
| Fouling behaviors | No | Improved |
| Grindability | Lower | Higher |
| Combustion activity | More active | Less active |
| Devolatilization activity | Less reactive | More reactive |
| Applications | Fuel and Char | Fuel and Char |
3. The forecasted Application of torrefied biomass
Torrefaction promotes the biomass to more uniform fuel that has further utilization in the following process:

(1) Co-firing with coal. Torrefaction can upgrade the fuel properties and change the combustion behaviors of raw biomass, thus promoting its potential to be used as fuel in the existing thermal conversion plants [22, 23], lower SO₂, CO₂, NOₓ emission levels and a reduction of soot in relation to the torrefaction processes [24-26]. Torrefaction is an emerging technology which enables greater co-firing rates of biomass with coal [27].

(2) Pelletization. Pelletization is applying a mechanical force to compact biomass residues or wastes(sawdust, shaving, chip or slab) into the uniformly sized solid particles such as pellets, briquettes and logs, thus increasing the volumetric energy density from the initial 40-200kg·m⁻³ to the final 600-1400kg·m⁻³, facilitating easy to rage and handling, reducing the transportation cost, and decreasing the moisture content [28, 29]. Torrefied biomass represents a high quality renewable energy commodity that can be used to substitute fossil fuels such as coal although the pelletization process will make up a great part of the cost. For full commercialization, torrefaction reactors still require to be optimized [30].

(3) Gasification. In a gasification process, biomass is converted to synthesis gas or syngas (i.e.H₂, CO) from fuels in an oxygen-deficient environment. On account of the improvement in biomass properties from torrefaction, torrefied biomass rather than raw biomass as a feedstock is expected to improve the gasification efficiency and lower the tar formation because of its high heating value and low volatiles content. As is reported, the torrefaction pretreatment of the biomass can be beneficial in terms of system thermal efficiency [31].

There are two routes for torrefied biomass used for gasification: external torrefaction and integrated torrefaction. External torrefaction is defined as the decentralized production of torrefied wood pellets and centralized conversion of the pellets by entrained flow gasification, with the benefit of producing a practically tar-free synthesis gas with nearly complete carbon conversion. Integrated torrefaction is defined as torrefaction integrated with entrained flow gasification. As Isaksson et al [32] reported, it is showed that the biomass to syngas efficiency can be increased from 63% to 86% (LHV-dry) while the total energy efficiency (biomass to methanol + net electricity) could be increased from 53% to 63% when switching from external torrefaction to integrated torrefaction. However the costs of the efficiency increase of integrated are as follows: 1) more difficult transport, storage and handling of the biomass feedstock (wood chips vs. torrefied wood pellets); 2) reduced plant size; 3) no net electricity production; and 4) a more complex plant design.

4. Conclusion
Torrefaction is an emerging technology which will accelerate the development of biomass utilization technology and finally realize the maximum utilization of biomass energy. Recently, there are two main technologies of biomass torrefaction—dry torrefaction and wet torrefaction, which are very different in process and products. Dry torrefaction is a conventional technology and easy to be realized and commercialized. The torrefied biomass is hydrophobic, with lower moisture contents, higher heating value and energy density, which is favor to combustion, pelletization and gasification. However, more intensive work should be done concerning biomass torrefaction for further utilization, especially, the customized torrefaction which is more practical for utilization.

Acknowledgements
This paper was financially supported by: Agricultural science and technology achievements conversion fund project of the ministry of agriculture (2015B020237010) and Guangdong province science and technology project (201607010138).

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