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Upgrading biomass fuels via wet torrefaction: A review and comparison with dry torrefaction

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ABSTRACT

Biomass pretreatment is an essential step prior to several thermochemical conversion processes. Wet torrefaction, a biomass pretreatment method in hydrothermal media or hot compressed water at temperatures within 180–260 °C, has been receiving a lot of attention because it possesses some advantages over other pretreatment methods. Apart from the undoubted benefits of upgrading biomass fuels to closer to coal properties, wet torrefaction has the capacity to work with wet or even extremely wet biomasses and enhance the ash removal from the biomass. The technology has recently attracted great interest from both academic groups and industrial companies. This review aims at providing a comprehensive overview of recent research and development activities in the field with focus on improvements in the chemical, physical and fuel properties of the solid product after wet torrefaction. Moreover, a brief introduction to dry torrefaction, a more conventional thermal pretreatment of biomass in the absence of oxygen under atmospheric pressure and in a temperature range of 200–300 °C, is also given and compared with wet torrefaction. Main differences in the properties of the solid products from the two torrefaction methods are also discussed.

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1. Introduction

Among the renewable energy sources, biomass is currently the major in use and accounts for approximately 10% of the global annual energy consumption [1]. However, the use of biomass for energy applications is not straightforward. Some disadvantages including its heterogeneity, low bulk density, high moisture content, low heating value, and poor grindability are limiting the use of biomass as fuel. These drawbacks make the conversion of biomass to produce heat and power challenging. In addition, they increase the cost of handling, transport, and storage of biomass fuels.

In order to overcome these aforementioned disadvantages of biomass, the fuel can be pretreated and upgraded via torrefaction. Currently, there are two torrefaction concepts: wet and dry. Both pretreatment techniques produce energy dense solid fuels with better chemical, physical and fuel properties than the raw biomass. The dry torrefaction (DT) concept came from the coffee production process, improving the grindability of coffee beans. Hence, it has some synonyms such as roasting, high temperature drying or mild pyrolysis. Between the two, DT has been intensively studied in the last couple of decades and a huge number of published papers and reports can be found in the literature. The wet torrefaction (WT) terminology came later, but it is developed from the concept of hydrothermal carbonization (HTC), invented by the German Nobel laureate Friedrich Bergius. Sometimes, WT has been used interchangeably with other similar concepts including HTC, hydrothermal (pre)treatment or hot compressed water (pre)treatment. Research and development activities in WT have increased recently due to some advantages of WT over DT. This review primarily aims at providing a comprehensive overview of the up-to-date research and development activities in WT technology, with focus on improvements in the chemical, physical and fuel properties of the solid product after the pretreatment. Moreover, comparisons of the two torrefaction concepts as well as key differences in the properties of their corresponding solid products are also discussed.

2. Problems coupled with biomass fuels

Bioenergy in the form of heat and power can be directly produced via biomass combustion and co-firing, or it can be indirectly stored in other forms of biofuel (e.g. bioethanol, biodiesel, biogas) for further use. There are many available options to convert biomass into thermal energy or biofuels via thermochemical (combustion, gasification, pyrolysis) [2–13], biological (anaerobic digestion, fermentation) [14–16] or chemical (esterification) [17–19] processes. Among these, direct combustion and co-firing with coal are currently the dominant technologies, which contribute to more than 90% of the global bioenergy deployment [35–39]. However, utilization of biomass for heat and power production is complicated due to inherent properties of this feedstock. The disadvantageous characteristics of biomass fuels and the consequent problems in the thermochemical conversion processes are listed in Table 1 [20]. These drawbacks make the direct combustion of biomass in existing coal-fired power plants for energy production more challenging. Alternatively, co-combustion or co-firing biomass with coal then becomes an attractive retrofit option to reach near-term targets for increasing the share of renewable energy and reducing CO_2 emissions [4,5,21]. However, it is still problematic because the chemical, physical and fuel properties of biomass, listed in Table 2 (adopted from [22–24]), are different from coal. It can be seen from the table that biomass has less fixed carbon and atomic carbon, more volatile matter, more oxygen, and more alkaline and alkaline earth metals in the ash than coal.

Table 1
Some disadvantages of biomass fuels utilized for thermochemical conversions (adopted from [20]).

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* *Require high feeding capacity*
Poor grindability	*Increase grinding energy* *More coarse particles*
Hygroscopic nature	*Absorb moisture during storage* *Increase risks of biological degradation*
High oxygen content	*Reduce the number of high energy C–H bonds* *Reduce the heating value and energy density* *Reduce the thermal stability*
High alkali metal content	*Make ash-related problems more serious*
Heterogeneity	*Wide variation in properties*

Table 2
Some chemical, physical and fuel properties of biomass and coal (adopted from [22–24]).

	Biomass	Coal
Proximate analysis (wt%)		
Moisture	2.5–62.9	0.4–20.2
Volatile matter	30.4–79.7	12.2–44.5
Fixed carbon	6.5–35.3	24.3–70.4
Ash	0.1–34.3	5.0–48.9
Ultimate analysis (wt%, dry and ash free)		
C	42.2–60.5	62.9–86.9
H	3.2–10.2	3.5–6.3
O	20.8–49.0	4.4–29.9
N	0.1–12.2	0.5–2.9
S	0.01–1.69	0.2–9.8
Ash analysis (wt% of dry ash)		
SiO_2	0.02–94.48	32.04–68.35
K_2O	2.19–63.90	0.29–4.15
Na_2O	0.09–29.82	0.09–2.90
CaO	0.97–83.46	0.43–27.78
MgO	0.19–16.21	0.31–3.98
Al_2O_3	0.10–15.12	11.32–35.23
Fe_2O_3	0.22–36.27	0.79–16.44
Other properties		
Mass density (kg/m^3)	250–954	1100–1300
HHV (MJ/kg)	14–21	22–34
Ignition temperature (°C)	144–190	190–322
Peak combustion (°C)	324–351	415–600
Particle size (μm)	~3000	~100

Although the ash content of biomass is lower than for coal, the chemistry of biomass ash is more complex than for coal due to higher percentages of alkaline and alkaline earth metals [24,25], which can cause serious problems in thermal conversion systems, such as agglomeration, deposition, corrosion, slagging and fouling [26,27]. Moreover, biomass has lower friability (or grindability), hydrophobicity, heating value and energy density compared to