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Review

Biomass upgrading by torrefaction for the production of biofuels: A review

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ABSTRACT

An overview of the research on biomass upgrading by torrefaction for the production of biofuels is presented. Torrefaction is a thermal conversion method of biomass in the low temperature range of 200–300 °C. Biomass is pre-treated to produce a high quality solid biofuel that can be used for combustion and gasification. In this review the characteristics of torrefaction are described and a short history of torrefaction is given. Torrefaction is based on the removal of oxygen from biomass which aims to produce a fuel with increased energy density by decomposing the reactive hemicellulose fraction. Different reaction conditions (temperature, inert gas, reaction time) and biomass resources lead to various solid, liquid and gaseous products. A short overview of the different mass and energy balances is presented. Finally, the technology options and the most promising torrefaction applications and their economic potential are described.

1. Introduction

The transition to a society driven by renewable energy sources such as solar, wind, biomass, tide, wave and geothermal energy next to energy savings becomes even more an important alternative in our energy consumption. According to the World Energy Outlook [1] renewable energy sources are expected to be the fastest growing energy sources. In this spectrum of several different energy sources biomass is the only source that is based on sustainable carbon.

In future energy scenarios an important role in the (renewable) energy supply has been addressed to biomass [1]. The unique position of biomass as the only renewable source as sustainable carbon carrier makes biomass an attractive energy source. Biomass can be converted into energy via thermo chemical conversions, biochemical conversions and extraction of oil from oil bearing seeds. Among various thermo chemical conversion methods gasification is the most promising. Gasification is the partial oxidation of carbonaceous feedstock above 800 °C to produce a syn-gas that can be used for many applications such as gas turbines, engines, fuel cells, producing methanol and hydrocarbons. Due to its higher efficiency, it is desirable that gasification becomes increasingly applied in future rather than direct combustion [2–4]. Coupling gasification with power systems increases the efficient use of thermal energy streams.

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Biomass as energy source shows some typical characteristics which makes it a special, but rather complicated fuel for the future. Biomass is available in a wide range of resources such as waste streams, woody and grassy materials and energy crops. Woody materials are preferred above food crops, because of several reasons. Woody materials contains much more energy than food crops, the amount of fertilizers and pesticides necessary for wood is much lower and the production of woody materials is much higher than for food crops which means that the land use becomes smaller. Another characteristic of biomass is its climate neutral behavior. If biomass is grown in a sustainable way, its production and application produces no net amount of CO_2 in the atmosphere. The CO_2 released by the application of biomass is stored in the biomass resource during photosynthesis and is extracted from the atmosphere which means a climate neutral carbon cycle of CO_2.

On the other hand, some biomass properties are inconvenient, particularly its high oxygen content, a low calorific value, a hydrophilic nature and a high moisture content. Also the energy production from biomass resources shows reduced overall energy efficiency due to photosynthesis. The overall energy efficiency from solar energy to biomass energy is 1–3% [5]. The high amount of oxygen also results in smoking during combustion. Other disadvantages of biomass are its tenacious and fibrous structure and its heterogeneous composition that makes process design and process control more complicated.

The use of biomass is also subjected to limitation of land, water and competition with food production. The agricultural production of biomass is relatively land intensive and involves high logistics costs due to low energy density of biomass. For biomass based systems a key challenge is to develop efficient conversion technology which can also compete with fossil fuels.

Torrefaction is a technology which can improve biomass properties and therefore offers some solutions to above problems. Torrefaction is a thermal pre-treatment technology to upgrade ligno-cellulosic biomass to a higher quality and more attractive biofuel. The main principle of torrefaction from a chemical point of view is the removal of oxygen with a final solid product: the torrefied biomass which has a lower O/C ratio compared to the original biomass.

The aim of this review is to present recent developments in the torrefaction technology. In the next part the main torrefaction characteristics such as operating conditions, mass – and energy balances and particle size reduction are described. An overview of torrefaction kinetics and decomposition mechanism is given in part three. Finally, this review shows the applications of torrefaction and an economic evaluation of the production of torrefied biomass pellets.

2. Torrefaction characteristics

2.1. *General process description*

Torrefaction is a thermal method for the conversion of biomass operating in the low temperature range of 200–300 °C. It is carried out under atmospheric conditions in absence of oxygen. Other names for the torrefaction process are roasting, slow- and mild pyrolysis, wood cooking and high temperature drying. In recent history torrefaction has only been applied to various types of woody biomass, but already around 1930 the torrefaction process was studied in France. The amount of publications on torrefaction is relatively small but increasing in the last few years. Literature about torrefaction of diverse biomass resources can be found, namely: maritime pine, chestnut, oak and eucalyptus, Caribbean pine [6], birch, pine, bagasse [7], bamboo [8], wood briquette [9], willow and beech [2,10,11], pedunculate oak [12], lauan wood [13], and oil palm wastes [14]. Just below 200 °C thermal methods are used for wood preservation [15–19], while torrefaction is for energy purposes.

Torrefaction is used as a pre-treatment step for biomass conversion techniques such as gasification and co-firing. The thermal treatment not only destructs the fibrous structure and tenacity of biomass, but is also known to increase the calorific value. Also after torrefaction the biomass has more hydrophobic characteristics that make storage of torrefied biomass more attractive above non-torrefied biomass, because of the rotting behavior. During the process of torrefaction the biomass partly devolatilizes leading to a decrease in mass, but the initial energy content of the torrefied biomass is mainly preserved in the solid product so the energy density of the biomass becomes higher than the original biomass which makes it more attractive for i.e. transportation.

A typical mass and energy balance for woody biomass torrefaction is that 70% of the mass is retained as a solid product, containing 90% of the initial energy content. The other 30% of the mass is converted into torrefaction gas, which contains only 10% of the energy of the biomass [20]. An energy densification with typically a factor of 1.3 can be attained. This is one of the main fundamental advantages of the torrefaction process. As the energy density of torrefied wood is significantly higher compared to untreated wood, larger transportation distances can be allowed. Another advantage of torrefied biomass is its uniformity in product quality. Woodcuttings, demolition wood, waste wood have after torrefaction quite similar physical and chemical properties.

Research focused on torrefaction has been started in France in the 1930s, but publications about this research are limited. Pentananunt et al. [21] studied the combustion characteristics of (torrefied) wood in a bench scale torrefaction unit. It was shown that torrefied wood has a significantly higher combustion rate and produces less smoke than wood. Also it was found that torrefied briquettes were practically water resistant and torrefaction appeared a good technique for upgrading briquettes. The structure of the torrefied biomass is changed in comparison to the raw biomass which makes it brittle and hydrophobic [22–24].

Ferro et al. [25] studied the effect of the raw material, temperature, residence time and nitrogen flow on the properties of the torrefied products. The experiments were performed in a reactor tube with pine, lucern, sugar cane bagasse, wood pellets and straw pellets. It was concluded that the type of biomass influenced the product distribution in its gas, liquid and solid ratio. The same research has been done for birch [7].