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Process optimization of combined biomass torrefaction and pelletization for fuel pellet production – A parametric study

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HIGHLIGHTS

- Single pellet experiment with parameters size, mass yield (torrefaction degree), moisture and die temperature.
- Temperature, moisture, mass yield and size explained 95% of the variation in compression work or friction.
- The higher mass yield, moisture and temperature, the lower compression and friction energy needed.
- Pellet strength more complex and about 80% of the variation explained by the tested parameters.
- Narrow window for pellet strength @ 4% moisture + 85% mass yield + 170 °C pelletizing temperature.

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ABSTRACT

Torrefaction of plant biomass has the capacity to produce a fuel with increased energy density and homogeneity, but there are reports that it changes the pelletizing properties of the biomass, making it more difficult to obtain high quality pellets. A parametric study was therefore conducted in which three key qualitative parameters, degree of torrefaction (250–300 °C), moisture content (0–10%) and pelletizing temperature (125–180 °C), were varied according to a five level fractional factorial design, also including particle size as a qualitative parameter. Pelletizing at 300 MPa (pellet densities: 1.0–1.2 mg/mm^3) was undertaken using a single pellet press and the responses recorded were compression work (W_{comp}), maximal force to overcome static friction (F_{max}), kinetic friction work (W_{fric}), single pellet dimensions and strength. Small particles reduced W_{comp} and F_{max}, but increased strength. As expected, all other parameters also had significant effects. In general, less energy was required for W_{comp}, W_{fric} and F_{max} at lower degrees of torrefaction and higher moisture contents and when pelletizing was conducted at higher temperatures. The process window to optimize pellet strength was narrow and, surprisingly, somewhat higher moisture content at higher degrees of torrefaction increased strength. This narrow production window in combination with feedstock variations may, in practical pelletizing situations, result in varying quality. Furthermore, the study illustrates that factorial experiments using single-pellet devices provide new insights that are of importance for the next generation of pelletizing of torrefied biomass.

1. Introduction

Heat and power production from renewables such as lignocellulosic biomass represent an increasing business sector and will result in strong growth of the global biomass trade, in particular biomass pellets [1]. Lignocellulosic biomass has, compared to conventional fuels, a relatively low bulk and energy density and a high degree of inhomogeneity. Thermal and mechanical pre-treatment technologies such as torrefaction and pelletization can increase energy density and homogeneity of biomass and reduce handling costs at the same time, as well as reducing transport costs [2,3].

During torrefaction, biomass is roasted in an oxygen depleted environment at temperatures between 240 and 320 °C (depending on the reactor type and technology), resulting in the removal of moisture and some of the volatiles, and leading to a reduction of the atomic ratios O/C and H/C in the resulting torrefied product [2,4]. In practice, this means that the majority of the calorific value of the biomass is retained within a fraction of the original mass, resulting in a biobased product with high specific energy, typically around 30% more energy per mass unit dry weight [2,5]. The

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physical properties of biomass fibers change significantly during torrefaction. Thermal degradation of the cell wall polymers, i.e. hemicelluloses, cellulose and to some extent lignin, transforms the biomass into a brittle material with hydrophobic properties [2]. In combination with pelletization, the aim is to produce a durable biobased fuel pellet of high energy density, with a high degree of homogeneity and hydrophobic characteristics that can, ideally, be handled and stored outdoors without weather (rain) protection. The brittleness and the reduced oxygen content of torrefied pellets make them an ideal candidate to replace coal with biomass in existing heat and power plants [2,6]. A number of studies have shown that torrefaction increases the efficiency of biomass combustion [7,8] and gasification [9] processes.

While pelletization of biomass is an established technology, with the annual global production of wood pellets estimated to be about 24.5 million tons in 2013 [10], torrefaction is still a new technology for the production of solid energy carriers, and is in a pre-commercial phase. Technological development has made significant progress during recent years and there are a number of initiatives and private companies in the process of scaling up production and starting to produce torrefied biomass pellets commercially [6]. Major technical challenges that have been identified regarding the development of torrefaction technologies are predictability and consistency of product quality, densification of torrefied biomass, heat integration and the flexibility associated with using different input materials [6].

During torrefaction the biomass polymers, especially hemicelluloses, are degraded mainly by depolymerization, demethoxylation, bond cleavage and condensation reactions [11]. An increasing degree of torrefaction has been shown to result in an increasing wall friction in the press channels of a pellet press and poorer mechanical properties [12–14].

Mechanical interlocking, solid bridges and intermolecular forces during pelletizing have been noted as important factors for bond formation, affecting the mechanical properties of a biomass pellet [15–18]. It has been suggested that the moisture content of the biomass is an important factor in this context due to its plasticizing effect and ability to reduce the glass transition temperature of cell wall polymers [19]. The modification of cell wall polymers, the removal of moisture and polar hydroxyl groups from the biomass during torrefaction, as well as reduced interlocking due to the brittleness of particles, are probably important factors decreasing the bonding properties of torrefied biomass when densified.

It has previously been shown that pelletizing parameters such as press channel dimension, moisture content, particle size and temperature have a significant effect on the friction generated in the press channel and thus on the energy required for pelletization [20]. These parameters also affect the pellets' mechanical properties. Different strategies are applied to counteract the effects of torrefaction on pelletizing properties such as increasing pelletizing temperature, adding moisture [21] and the addition of processing aids with lubricating properties to improve pellet quality and ease processing [22]. Overall, the aim is to reduce energy consumption while maximizing the capacity and quality of the pellet production processes.

Most process optimization today is undertaken experimentally in either a lab or in pilot scale units and is based on trial and error. This is mainly due to a lack of understanding of the correlations between torrefaction and pelletization parameters and their effect on pellet quality (strength) and process energy consumption (compression and friction). To address this, the present study maps the combined effects of key parameters of torrefaction and pelletization on the pelletizing process and the resulting pellet quality.

2. Materials and methods

2.1. Biomaterials

Norway spruce (*Picea abies* Karst.) grown in Värmland, Sweden, was used for the torrefaction. The spruce was harvested during fall 2011 and then sawn and dried in a wood kiln. Thereafter the sawn timber was trimmed and the pieces trimmed off were shredded. The shredded material was then sieved (Sizer typ E0554, Mogensen, Sweden) to separate it into different sizes; the material used for torrefaction was larger than 4 mm but less than 8 mm. The material was stored dry for 12 months before torrefaction.

2.2. Experimental design

A D-optimal fractional factorial experiment with four parameters was designed. First, a qualitative parameter "particle size" was used with two classes ("small" < 0.5 mm, and 0.5 mm < "big" < 2 mm). The following were quantitative parameters at five levels: torrefaction degree (within the range 250–300 °C resulting in mass yields from 90.5% down to 71.1% based on dry matter); moisture content of materials entering the pellet press (dry to 10%); and, finally, die temperature during pelletizing (125–180 °C). The center point for the larger particles was repeated three times. In all, 29 separate experiments were run (Table 1). The experimental design allowed analysis of the dependency between different process parameters on pellet quality and forces occurring in the press channel of a pellet press.

2.3. Torrrefaction

A bench scale torrefaction reactor was constructed to enable the production of materials with different degrees of torrefaction. A box made of stainless steel, with a volume of about one litre, and fittings for the inflow and outlet of gasses was used as a reactor. The reactor was inserted in a programmable muffle furnace with a maximum output of 3000 W (Carbolite furnaces, Carbolite UK) and flushed with nitrogen during the whole process at a rate of 0.5 L/min using a pressure and flow regulator. For temperature monitoring, a thermocouple was installed at the center of the reactor and connected to a logger (TESTO 735-2, Testo, Germany), and another thermocouple was installed in the furnace to control the heating of the furnace. The heating was controlled by the furnace thermocouple instead of the thermocouple placed in the middle of the reactor. This minimized the risk that the furnace temperature would overshoot, which could result in a torrefaction degree gradient in the reactor caused by higher temperatures at the reactor sides. Five different temperatures were chosen resulting in different degrees of torrefaction (Table 1). The degree of torrefaction is here defined as mass yield in percentage based on dry mass before and after torrefaction.

The material was dried at 105 °C for 16 h before torrefaction. A sample consisting of about 130 g of the dried material was placed in the reactor. The reactor was heated to the set temperature at a heating rate of 3.8–7.3 °C/min depending on the temperature set (a higher temperature resulted in a higher heating rate) and with a declining heating rate closer to the set temperature. Then the set temperature was maintained for 60 min. Directly thereafter the reactor was quenched with cold tap water to stop the torrefaction process. Amount of C, H, O, N, S and ash in the torrefied materials as well as their calculated gross calorific values are presented in Table 2.

2.4. Milling and sieving

After torrefaction, the material was milled in a knife mill (Retsch SM2000, Retsch, Germany) over a 6 mm sieve. To achieve the