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Research paper

Comparative net energy ratio analysis of pellet produced from steam pretreated biomass from agricultural residues and energy crops

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ABSTRACT

A process model was developed to determine the net energy ratio (NER) for the production of pellets from steam pretreated agricultural residue (wheat straw) and energy crops (i.e., switchgrass in this case). The NER is a ratio of the net energy output to the total net energy input from non-renewable energy sources into a system. Scenarios were developed to measure the effects of temperature and level of steam pretreatment on the NER of steam pretreated wheat straw and switchgrass pellets. The NERs for the base case at 6 kg h^{-1} are 1.76 and 1.37 for steam-pretreated wheat straw and switchgrass-based pellets, respectively. The reason behind the difference is that more energy is required to dry switchgrass pellets than wheat straw pellets. The sensitivity analysis for the model shows that the optimum temperature for steam pretreatment is 160 °C with 50% pretreatment (i.e. 50 % steam treated material is blended with the raw biomass and then pelletised). The uncertainty results for NER for steam pretreated wheat straw and switch grass pellets are 1.62 ± 0.10 and 1.42 ± 0.11, respectively.

1. Introduction

One of the ways to reduce the growing concerns of greenhouse gas (GHG) emissions is to substitute fossil fuels with sustainable biomass feedstocks like agricultural residue (wheat straw) and forest residue. The economics of biomass-based power generation have been evaluated earlier by several authors [1–8]. One of the key barriers to large-scale biomass use is the supply of consistent quality feed to biomass-based facilities [3,9,10]. The low energy density and yield of biomass-based feedstock limit the use of biomass. The pelletization of biomass is a process through which the calorific value of biomass can be increased. Pelletization, which can increase energy density, can be implemented to reduce transportation costs since the high energy density means that less feedstock needs to be transported [11]. Pelletization reduces transportation costs by increasing volumetric density. In addition, this technology allows the free flow of fuels, which simplifies loading and unloading [11]. There have been a number of studies on pelletization and economics of conventional pellet production using lignocellulosic biomass (e.g., forest residues, wheat straw, sawdust) [3,4,12]. Also studies have assessed energy consumption in pellet production [13].

While regular pelletization improves the energy density of the biomass, significant improvement is required in biomass densification to make it lucrative to biomass-based facilities. The higher heating value of coal is 26 MJ kg^{-1}, while that of pelletized biomass is 16–18 MJ kg^{-1}. The higher heating value can be improved through biomass pretreatment before pelletization, as suggested by Tooyserkani and Lam [9,10]. Typically, this process includes steam pretreatment, ammonia pretreatment, and acid catalyzed pretreatment [14]. The steam pretreatment process is an additional process added to the pelletization supply chain to improve the calorific value and bulk density of biomass, which in turn reduces transportation and handling costs [15,16].

The effect of steam pretreatment, also known as Masonite technology [10], at temperatures ranging from 180 to 240 °C, is decompression of the saturated steam from the Stake/Masonite gun environment to cause rapid expansion, which ruptures the cellular structure [17,18]. The steam pretreatment and pellet production processes involve energy for drying, grinding, pelleting,

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and steam pretreatment. The pelletization process, along with the steam pretreatment process, has been explained in detail in our previous work [19].

While a number of authors have previously estimated process net energy ratio (NER) for different biomass pathways [13,20–22], the NER for steam pretreated biomass-based pellet production has received minimal discussion in the literature. The net energy ratio (NER) is the ratio of net energy output to the total energy input from non-renewable sources. In an earlier study, the authors evaluated the NER for pellets produced from steam pretreated forest residues [19], but the process energy requirements and NERs of pellets produced from wheat straw and switchgrass have not been evaluated so far. There is a need to evaluate the NER from a life cycle point of view for these feedstocks; this evaluation could help in further development of the most efficient technology. In light of this gap in the literature, the main objectives of this study are to develop a process model for steam pretreatment of agricultural residues and energy crops for pellet production, evaluate the energy and mass balance of the steam pretreated pellet production process, and estimate the NER of the process.

2. Methodology

This study employs process modeling of the pellet production processes from wheat straw and switchgrass. The pellet production process model is built based on experimental results. The model evaluates the NER of steam pretreated pellets from two feedstocks and compares it with the NER of regular pellet production. Regular pellet production refers to pellet production without steam pretreatment. The process model evaluates the energy requirement of two processes, the steam pretreatment of biomass for pellet production and regular pellet production.

The process simulation model tool, Aspen Plus [23] was used for this study. The focus was on mass and energy balance. The process model of steam pretreatment consists of a number of unit operations that are joined by the mass and energy streams. Experimental work on the steam pretreatment of wheat straw and energy crops was used to validate the process model. The specific energy consumption of each unit operation was calculated using the developed process model. The model was also used to create a correlation between the energy consumption of small-scale steam pretreatment and regular pellet production processes for different feedstocks. The NER of the two processes was then evaluated and comparatively analyzed.

The unit operations of steam pretreated pellet production, in order of highest to lowest energy consumption, are the dryer, the steam pretreatment process, and the pelletization process. The existing process models for these are shown in Fig. 1. The unit operations in the process model are chosen based on the operating conditions of the experimental units described above.

The pelletization process starts with the harvesting and collection of wheat straw and switchgrass in bales form and transporting them to the pellet mill [24]. The mean water mass fraction of the wheat straw and switchgrass is around 10–14%. The biomass collected from the forest is first chopped in a grinder to reduce particle size. The feedstocks are ground in a hammer mill to a particle size of 3.2 mm or less [25]. The particle size can be changed in the hammer mill by varying the mesh screen size.

The feedstock is then passed through a pellet mill with a roller that extrudes the feedstock and pushes it though a die hole, compressing it into pellets. The pellet mill feed rate is adjusted with its service life and is done purposely to ensure pellet quality, since a high feed rate impacts the compression provided by the die and reduces pellet density [4]. A pellet mill's efficiency depends on a number of parameters like die temperature, die and roller configuration, and pressure [26]. Once pellets are formed, they are air-cooled from a temperature of 95–100 °C–25 °C.

Experimental work of steam pretreatment carried out in

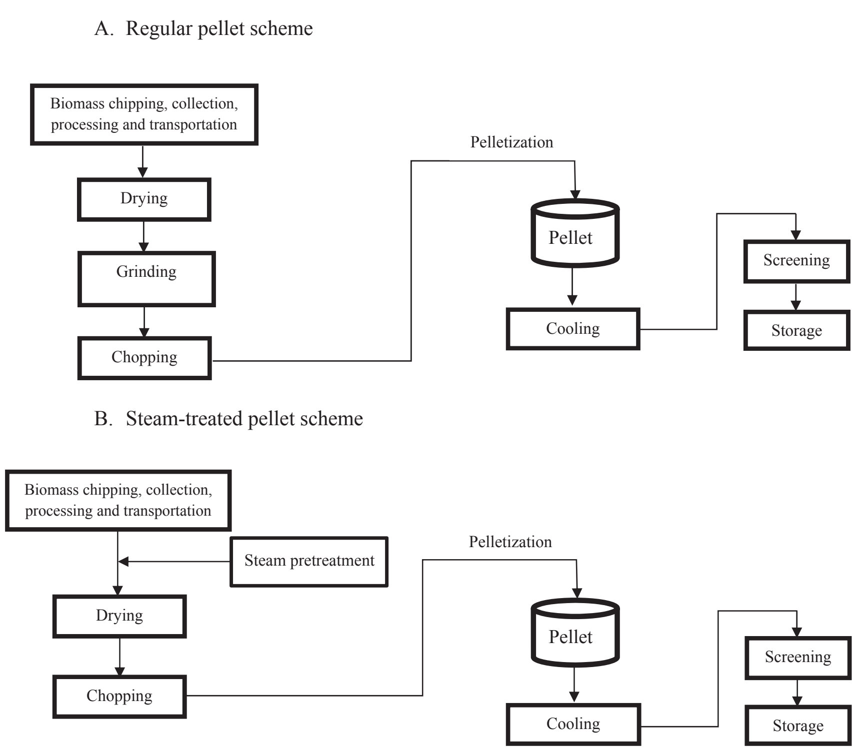

Fig. 1. Production chain of regular pellets and steam-treated pellets.