



Research paper

Net energy ratio for the production of steam pretreated biomass-based pellets



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ABSTRACT

A process model was developed to determine the net energy ratio (NER) for both regular and steam-pretreated pellet production from ligno-cellulosic biomass. NER is a ratio of the net energy output to the total net energy input from non-renewable energy source into the system. Scenarios were developed to measure the effect of temperature and level of steam pretreatment on the NER of both production processes. The NER for the base case at 6 kg h⁻¹ is 1.29 and 5.0 for steam-pretreated and regular pellet production respectively. However, at the large scale NER would improve. The major factor for NER is energy for steam and drying unit. The sensitivity analysis for the model shows that the optimum temperature for steam pretreatment is 200 °C with 50% pretreatment (Steam pretreating 50% feed stock, while the rest is undergoing regular pelletization). Uncertainty result for steam pretreated and regular pellet is 1.35 ± 0.09 and 4.52 ± 0.34 respectively.

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1. Introduction

The primary sources of renewable energy are wind, geothermal heat, sunlight, water and biomass. Renewable energy constitutes 16.7% of global energy consumption. About 8.7% of the total renewable energy consumption is from biomass. Biomass is a source of renewable energy collected from plant origin. The main sources of biomass are whole forest, forest residue, agricultural residues and purposely grown crops. The biomass is collected from the field and undergoes conversion to produce bio-fuels like bio-ethanol, pellets and bio char. The use of ligno-cellulosic biomass (e.g. wood residues and agriculture residues) for bio-energy and bio-fuels in place of fossil fuels can help to address a number of global problems, such as the dependence on fossil fuels and high GHG emissions from conventional fuel, and at the same time have a positive socio-economic effect by creating jobs [1].

The challenge for the use of ligno-cellulosic biomass is limited because of its low heating value and low yield per unit area of biomass [2]. Ligno-cellulosic biomass feed stocks used for bio-

energy and bio-fuels production have low bulk density in the range of 75–200 kg m⁻³ and have a high mean water mass fraction (in the range of 14–50%) [3]. However, regular wood pellets with high bulk density (600–800 kg m⁻³), low mean water mass fraction (5–8%) and regular shape and size make a lucrative feedstock for bio-refineries. Pellets are densified and compressed form of biomass which has less moisture and higher energy density. The pellet production supply chain currently consists of drying, grinding, pelleting, cooling, screening, and bagging. All of these processes are energy intensive and significantly impact specific energy consumption. Detailed unit operation reviews of the pelletization processes have been provided elsewhere in the literature [4–8].

The pelletization process starts with the collection of forest residues, which are sent to a shredder to be formed into wood chips. The wood chips that will be pelletized are transported to the pellet mill. The mean water mass fraction of these woods chips is around 50%. These chips require drying before being comminuted and pelletized. The size of the dryer can affect energy consumption significantly. The dryer unit used most often in pellet production plants is a rotary drum dryer [8,9]. Once dry, chip mean water mass fraction is around 8–10% [9]. The dry chips are fed to a hammer mill

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for grinding and ground to a particle size of 3.2 mm or less [3]. The particle size can be changed in the hammer mill by varying the mesh screen size [10]. In summary, there are two steps in reducing forest residue particle size: chopping by shredder followed by grinding by hammer mill.

Pelletization of the feedstock is done by passing the feedstock through a pellet mill with a roller that extrudes the feedstock and pushes it through a die hole, compressing it into pellets. The feed rate of pellet mills are adjusted with their service life; this variation of feed rate is done purposely to ensure pellet quality since high feed rate impacts the compression provided by the die reducing pellet density [11]. A pellet mill's efficiency depends on a number of parameters like die temperature, die and roller configuration, and pressure [9]. Once pellets are formed, they are cooled from a temperature of 95–100 °C to 25 °C using air.

Recently, densified biomass has been receiving significant attention. Improving the physical and combustion characteristics of densified biomass could result in a superior quality product [1,4]. Ligno-cellulosic biomass-based pellets are considered to be carbon neutral, which means that the emissions from their combustion are offset by the carbon absorbed by the plants during their re-growth [11]. Furthermore, regular pellet bulk density is 4–10 times higher than that of the ligno-cellulosic biomass received at the gate [11] and hence pellets are much easier to handle and transport. These above-mentioned factors make regular pellets a lucrative option for bio-energy and bio-fuels.

Biomass pellets have higher energy content, burning efficiency and leads to lower emission [12]. Current Canadian pellet production is 1.3 Mega tonnes per year with plants running at 65% capacity of the maximum capacity of plant. The produced pellets were exported mostly to Europe, the USA, and Japan for electricity production [1]. Compared to Canada, the USA has seen a much higher and more rapid growth in pellet production and export of wood pellets than Canada [13]. A breakdown of Canadian pellet production by province shows that 65% of the country's production capacity is from British Columbia (B.C.), followed by Alberta, Quebec, New Brunswick, Nova Scotia, and Newfoundland, which together contribute 35%. B.C. pellet plants are larger than those in Eastern Canada simply due to higher demand in B.C. The pellets produced in Canada are mainly used for export to Europe, the USA, and Japan [1].

The biomass feedstock supply logistic cost is around 30–50% of the total bio-energy production cost [14]. It is essential to optimize the preprocessing of biomass into densified pellets for cost-effective bio-energy production. Regular pellet production leads to some improvement in bulk density and calorific value. But it fails to increase it significantly. Hence, the need for different pretreatment processes arises to improve the bulk density and calorific value. Further improvement can be achieved by increasing the yield and reducing the energy required for preprocessing. Two major technical problems during preprocessing need to be addressed. The focus of our research has been to improve the heating value and evaluate the specific energy consumption for both regular and steam-pretreated pellet production.

The steam pretreatment process pretreats the material by using saturated steam, thereby adding another process, but the entire supply chain remains the same as that of regular pelletization process. Even though pelletization leads to energy densification and bulk density improvement, pellet durability and energy density need to be improved further to ensure effective storage and handling [15,16]. The real effect of steam pretreatment, also known as Masonite technology [17], 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 – as pressurized water in the lumen

expands, flashes and ruptures the cell walls when the external pressure is reduced [18]. Steam pretreatment involves high pressure saturated steam ranging from 150 to 500 psi (1.034–3.447 Mpa) to heat biomass to rupture the rigid structure of the biomass. A steam pretreatment unit can be operated in batch or continuous mode. A batch reactor is usually used in a laboratory to pre-treat biomass while a continuous reactor is used by industry (Sun Opta Bioprocess Inc. is one such company that uses a continuous reactor). The commercialized continuous system has been adapted for a variety of biomass feed stocks including forestry and agricultural residues like wheat straw, corn stover, switch grass, and wood chips.

Previous studies have assessed different pretreatment methods like torrefaction, chemical pretreatment and steam pretreatment. Based on these studies, steam pretreatment leads to improved mechanical strength, hydro-phobicity, and energy density of wood pellets [16,19,20]. The previous studies also showed that the mean water mass fraction of the produced solid increased by up to two times after steam pretreatment [16,20]. The additional moisture absorbed during steam pretreatment requires additional drying energy [6]. There are limited data available on the specific energy consumption of the steam pretreatment process and the effect of steam pretreatment at different temperatures on the net energy ratio (NER) of the entire process. The net energy ratio (NER) is a ratio of the net energy output to the total net energy input from non-renewable energy source into the system. Similarly, there are no assessments on the varying scale of application of steam pretreatment in pellet production.

The purpose of our research is to develop a process model to evaluate the specific energy consumption of steam pretreated pellet production process and compare it to regular pellet production process at various scales. This research will also quantify the energy density benefit from steam pretreatment of pellet production and the impact of the steam pretreatment on the process NER. Several authors have previously estimated NER for various biomass pathways [21,22], however none of these have looked at NER for steam pretreated biomass-based pellet production. Based on the gap in literature, the three main objectives of this research are to:

- Develop a process model for steam pretreatment of ligno-cellulosic biomass for pellet production
- Evaluate energy and mass balance of steam pretreated pellet production process
- Calculate the NER of the production process of steam pretreated pellet production process

2. Methodology and model details

The process simulation for the study was carried out through Aspen PLUS [23] with a focus on mass and energy balance. The entire steam pretreated pellet production process is broken down into several unit operations, which are then integrated by using mass and energy streams. The models are then validated with data collected through experimental work on steam pretreatment of ligno-cellulosic biomass. With the process model developed for this research, the specific energy consumption of each unit operation can be evaluated at the small scale. The model will be used to create a correlation between the energy consumption of the two process methods at the small scale and to use this correlation to predict the NER for the two processes at the large scale. The research work and the developed model will help to evaluate the NER of the steam pretreatment process and compare it with the NER of the regular pellets.

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