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Energy Procedia 142 (2017) 395–400

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Process modeling for torrefaction of birch branches

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Abstract

This work presents a complete biomass torrefaction model for Norwegian birch branches. The model can provide detailed distribution of both the main and by-products from the torrefaction process. Reduction in mass and energy yields as well as increase in heating value of the torrefied biomass with increasing torrefaction temperature are observed. Simulation results show good agreement with available experimental data in the literature. Furthermore, the overall energy consumption and the process energy efficiency can be also estimated, which is essential for process up-scaling. It reveals that drying accounts for 76-81% of the total heat demand. More importantly, the process energy efficiency reduces with increasing temperature thus torrefaction at high temperatures is not advisable. The information obtained from the model is important for industrialization and commercialization of the torrefaction process.

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Keywords: Torrefaction; Biomass fuels; Process modeling; Process optimization; Energy efficiency.

1. Introduction

Torrefaction is a thermochemical pretreatment of biomass at temperatures of 200-300 °C in an inert atmosphere and under atmospheric pressure [1-4]. The process can produce a solid fuel with superior fuel properties compared to untreated biomass. Torrefied biomass has increased heating value, better grindability, and more hydrophobicity, which makes the fuel more readily suitable in subsequent conversion processes such as pyrolysis, liquefaction,

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Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.
10.1016/j.egypro.2017.12.062

gasification and combustion. Besides the main solid product, a number of by-products including water, carbon dioxide (CO_2), carbon monoxide (CO), and various organic compounds can be obtained after torrefaction. They can be classified into two groups: non-condensable and condensable volatiles, although they are all volatiles when formed at the torrefaction temperature. The former are permanent gases, while the latter becomes liquid after cooled to room temperature.

Recently, research and development activities on biomass torrefaction have been very active to look at the torrefaction characteristic of a wide range of biomass species and to investigate the effects of torrefaction parameters (e.g., temperature and residence time) on the fuel properties of the torrefied products [5-10]. However, most of them are experimental studies, from which information for up-scaling the process is limited. In order to fulfill the research gap between academia and industry, process modeling studies are required.

This work aims to build a complete torrefaction model for Norwegian birch branches using a commercial simulator. The model can provide a detailed distribution of main torrefied products and by-products at various torrefaction conditions. The heating value of the main solid product after torrefaction can be predicted and are compared with available experimental data. More importantly, the overall energy consumption and the process energy efficiency are estimated and presented.

Table 1. Description of all units and streams in the torrefaction model.

Unit or stream	Classification	Description	Operating temperature (°C)
DRY-AIR	Cold stream	Air at ambient temperature	25
HX-AIRDR	Heater	Drying air heater	–
HOT-AIR	Hot stream	Hot inlet drying air	180
DRIER	Block	Drying unit	–
EXHAUST	Hot stream	Hot outlet drying air	110
HX-EXH	Cooler	Outlet drying air cooler	–
COLD-AIR	Cold stream	Cooled drying air	50
DRY-BIOM	Hot stream	Hot dried biomass	110
N2-COLD	Cold stream	Nitrogen at ambient temperature	25
TOREFIER	Block	Torrefaction unit	240–300
TOR-BIOM	Hot stream	Torrefied biomass stream	240–300
BYPROD	Hot stream	By-products stream	240–300
HX-COOL	Cooler	Product cooler	–
PROD	Cold stream	Final torrefied biomass product	50
COMB-AIR	Cold stream	Air fed to combustor	25
COMBSTOR	Block	Combustion unit	–
HOT-FG	Hot stream	Hot flue gas	–
HX-FG	Cooler	Flue gas cooler	–
COLD-FG	Cold stream	Cold flue gas	50

2. Methodology

2.1. Torrefaction process flow diagram

The flow diagram of the torrefaction model in Aspen Plus v8.8 is illustrated in Figure 1. Description of all units and streams are presented in Table 1.

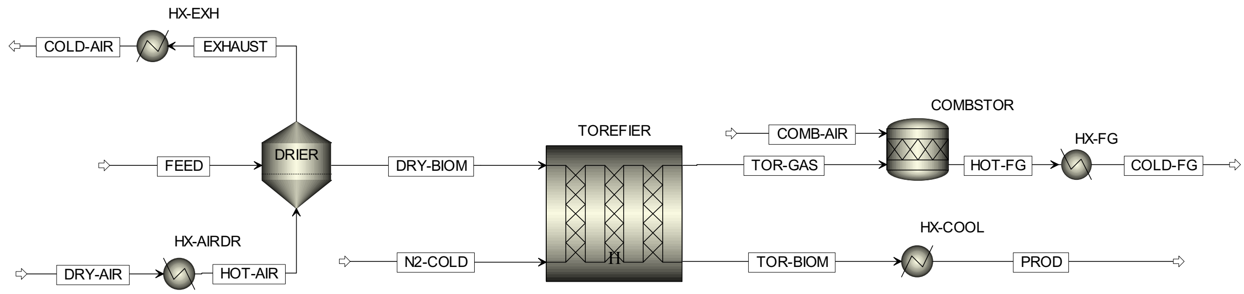

Fig. 1. Flow diagram of the torrefaction model.

2.2. Feedstock and torrefaction reactions

Norway birch branches, i.e. a forest residue, were chosen as the feedstock in this study. Available data for the fuel properties of the feedstock are adopted from another work [11] and presented in Table 2. The initial feedstock was assumed to have a moisture content of 50%, which is close to its measured value (56.31 ± 1.93 wt%) directly after harvesting, and the moisture content has been set to reduce to 10% prior to entering the torrefaction reactor.

Table 2. Fuel properties of feedstock.

	Moisture content[a]	Proximate analysis[b]			Ultimate analysis[b]			
		Ash	VM	FC	C	H	N	O
Norway birch branches	50	0.64	89.73	9.63	48.24	6.15	0.16	44.81

[a]wt%, wet basis; [b]wt%, dry basis

If it is assumed that biomass contains only carbon, hydrogen, oxygen, nitrogen, sulfur and ash, a general chemical formula for biomass is $C_aH_bO_cN_dS_eA_f$, where C, H, O, N, and S represent the elements and A represents ash in biomass, and subscript letters are calculated from the ultimate analysis of the fuel. A torrefaction reaction, based on a previous study by Bates and Ghoniem [12], can be given as in Eq. (1):

$$C_aH_bO_cN_dS_eA_f \xrightarrow{Temperature,\ time} Y(g)C_iH_jO_kN_lS_mA_n + \begin{cases} \alpha(g)\ H_2O \\ \beta(g)\ CO_2 \\ \gamma(g)\ CO \\ \delta(g)\ CH_4O \\ \varepsilon(g)\ CH_2O_2 \\ \zeta(g)\ C_2H_4O_2 \\ \eta(g)\ C_3H_6O_2 \\ \theta(g)\ C_3H_6O_3 \\ \vartheta(g)\ C_5H_4O_2 \end{cases} \quad (1)$$

where $C_aH_bO_cN_dS_eA_f$ and $C_iH_jO_kN_lS_mA_n$ represent the raw and torrefied biomass; Y is the mass yield of the torrefied biomass; the Greek characters denote the mass yields of the corresponding by-products.

2.3. Assumptions

Some assumptions are made for the process simulations:

- The stream class used in the model is MIXCISLD, in which raw and torrefied biomass are considered as non-conventional solids.
- The properties method is Redlich-Kwong-Soave (RKS).
- All calculations are in steady-state.

- The system operates at atmospheric pressure and all pressure drops are neglected.
- Air consists of 79% nitrogen and 21% oxygen on molar basis.
- The ambient temperature is 25 °C, i.e. supplied air and nitrogen enter corresponding blocks at 25 °C.
- The hot streams (EXHAUST, HOT-FG, and TOR-BIOM) are cooled to 50 °C.
- Heat losses are assumed to be 10% of the heat produced from or supplied to blocks.

3. Preliminary results and discussion

3.1. Products distribution and characterizations

The simulation was carried out at different torrefaction temperatures, from 240 to 300 °C. A torrefaction time of 30 min was selected and kept constant because the effect of time is less pronounced than that of temperature. In addition, a flow rate of 200 kg wet feedstock per hour was chosen for this simulation.

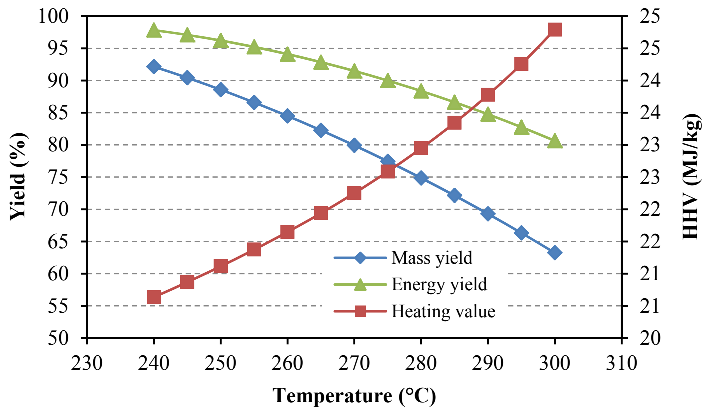

Fig. 2. Plots of mass yield, energy yield and heating values of torrefied biomass at different temperatures.

Simulation results for the mass and energy yields as well as the heating values of the torrefied biomass at different temperatures are presented in Fig. 2. It can be seen from the figure that both the mass and energy yields of the torrefied biomass decrease while its heating value increases with increasing torrefaction temperature. When the temperature increases from 240 to 300 °C, the mass and energy yields reduce respectively from 92.2 to 63.2% and from 98.7 to 80.6%; on the other hand, the heating value is raised from 20.6 to 24.8 MJ/kg. Increased heating value of torrefied biomass is attributed to changes in their elemental composition.

Fig. 3 presents the mass yield distribution of the by-products after torrefaction at different temperatures. It can be seen from the figure that more by-products are produced when increasing the torrefaction temperature, which is consistent with the decreasing mass yield trend of the torrefied biomass. Among the by-products, water is the most dominant (4.1-13.2%), followed by carbon dioxide (2.4-4.8%). Methanol is a minor component at low temperatures but its contribution increases greatly and is even higher than carbon dioxide at high temperatures. Other by-products play minor parts because most of them account for less than 4.4% at the highest temperature (i.e., 300 °C).

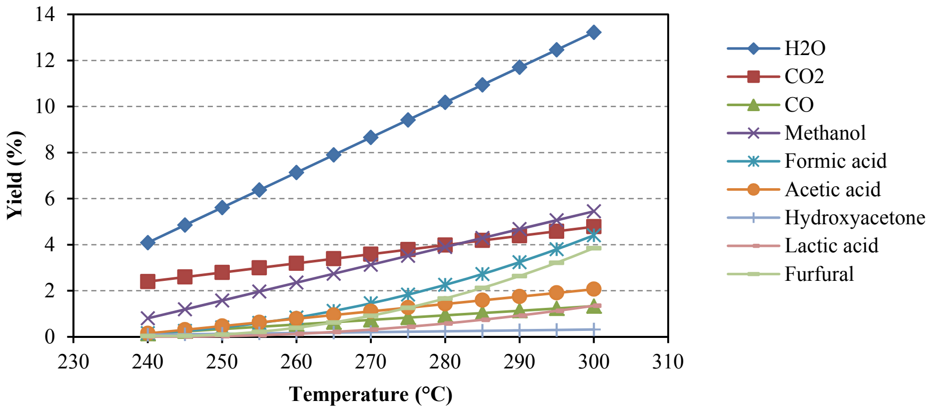

Fig. 3. Distribution of torrefaction by-products at different temperatures.

3.2. Heat required/produced and thermal energy efficiency

The heat required and produced as well as thermal energy efficiency of the torrefaction process at different temperatures are extracted from the simulations and presented in Table 3.

Table 3. Heat required/produced and thermal energy efficiency of torrefaction process.

Torrefaction temperature (°C)	Heat required/produced (kW)			Energy efficiency (%)
	Drying	Torrefaction	Utilities	
240	-100.9	-23.1	32.4	92.9
245	-100.9	-23.6	35.2	92.7
250	-100.9	-24.1	38.6	92.5
255	-100.9	-24.7	42.5	92.2
260	-100.9	-25.3	47.0	91.9
265	-100.9	-25.9	52.1	91.6
270	-100.9	-26.6	57.7	91.3
275	-100.9	-27.3	63.9	90.9
280	-100.9	-28.0	70.6	90.5
285	-100.9	-28.8	77.9	90.1
290	-100.9	-29.6	85.7	89.6
295	-100.9	-30.5	94.1	89.1
300	-100.9	-31.3	103.0	88.5

It can be seen from the table that it requires about 100.9 kW to dry 200 kg feedstock per hour from 50% to 10% moisture. In other words, drying accounts for 76-81% of the total heat required for the whole process. This observation is in good agreement with other literature showing that drying is an energy intensive step [13-15]. Because the feedstock flow rate is kept constant, the drying energy is thus unchanged with the torrefaction temperature. The table also reveals that sustaining the torrefaction process needs only 19-24% of the total heat required for the whole process, i.e., 23.1-31.3 kW, depending on the torrefaction temperature: the higher the torrefaction temperature is the more energy it requires. Compared to the drying energy, heat demanded for torrefaction is 3.2-4.3 times less. Another important information is the utilized energy, which is from 32.4 kW at a torrefaction temperature of 240 °C to 103.0 kW at a torrefaction temperature of 300 °C. More energy is collected from the utilities at higher torrefaction temperature because more by-products are produced and thus more heat is extracted at HX-COOL. Furthermore, Table 3 also exposes a decreasing trend in the thermal energy efficiency of the process when increasing the torrefaction temperature, which is due to increased heat loss with increasing torrefaction temperatures.

4. Conclusion

A complete torrefaction model has been built in the Aspen Plus v8.8 software. Norwegian forest residue (birch branches) was chosen as the feedstock. The model is capable to provide the distribution of both the torrefied biomass and by-products. Simulation results show good agreement with available data in the literature. Increasing the torrefaction temperature leads to reduction in both the mass and energy yields of the torrefied biomass but increase in the heating value. The model also reveals that drying accounts for 76-81% of the total heat demand. More importantly, the process energy efficiency reduces with increasing temperature, thus torrefaction at high temperatures is not recommended. The information obtained from this work would be important for industrialization and commercialization of the torrefaction process.

Acknowledgements

This research was supported by the Chung-Ang University Research Grants.

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