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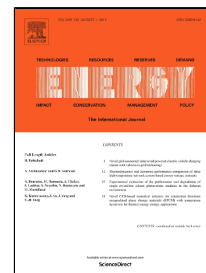
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Process modeling and optimization for torrefaction of forest residues

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Abstract

This work aims to build a comprehensive biomass torrefaction model, which can provide a wide range of information essential for industrialization and commercialization of the process. Norwegian forest residue (birch branches) was chosen as feedstock. The model is capable of presenting detailed distributions of main and by-products from the torrefaction process. In addition, important fuel properties (ultimate analysis and heating value) of the main solid product after torrefaction can be predicted. The model is validated and simulation results show good agreement with available experimental data in the literature. Reduction in mass and energy yields as well as improvement in heating value of torrefied biomass with increasing torrefaction temperature are observed. Trends for carbon, oxygen and hydrogen contents are also consistent with other experimental works. Moreover, overall energy consumption and process energy efficiency can be estimated from the model. It reveals that drying accounts for 76-80% of the total heat demand. Furthermore, the process energy efficiency reduces with increasing temperature, thus torrefaction at high temperatures is not advisable. More importantly, process optimization shows that optimal conditions for torrefaction of birch branches are 30 min holding time and a temperature between 275 and 278 °C.

Nomenclature

Abbreviation or Symbol	Unit	Description
D_E	–	Energy densification
E	kW	Energy required for sustaining the process
F_{feed}	kg/h	Mass flow rate of the feedstock
F_{prod}	kg/h	Mass flow rate of the solid product
FC	–	Fixed carbon
HHV_{raw}	MJ/kg	Higher heating value of the raw biomass
HHV_{tor}	MJ/kg	Higher heating value of the torrefied biomass
LHV_{raw}	MJ/kg	Lower heating value of the raw biomass
LHV_{tor}	MJ/kg	Lower heating value of the torrefied biomass
LHV_{feed}	MJ/kg	Lower heating value of the feedstock
LHV_{prod}	MJ/kg	Lower heating value of the solid product
m_{raw}	kg	Mass of the raw biomass
m_{tor}	kg	Mass of the torrefied biomass
VM	–	Volatile matter
wt%	–	Weight percent
Y_E	%	Energy yield
Y_M	%	Mass yield
η_P	%	Process energy efficiency

1   Introduction

Currently, biomass is recognized as an important renewable energy source and contributes to approximately 10% of the global energy consumption [1]. The use of bioenergy derived from biomass instead of fossil fuels can increase energy security and support more sustainable development in many countries. Biomass can be used directly or blended with coal in combustion or co-combustion systems to produce heat and power. In addition, it can be converted into solid, liquid and gaseous fuels via e.g. pyrolysis, liquefaction and gasification, respectively, which offer more end-use options from biomass [2-4]. However, the utilization of biomass for energy application is not always straightforward due to inherent chemical and physical properties of the fuel. Compared to coal, biomass has lower bulk density, higher moisture content, inferior heating value, and poorer grindability [5-8]. Ideally, current conversion systems using coal can be switched to biomass without or with minor modifications. Nevertheless, the drawbacks of biomass restrain the deployment of bioenergy and also contribute to increase the logistical costs of the fuel. In order to overcome these problems, it normally requires a pretreatment of the biomass prior to further conversion processes.

Torrefaction is a thermochemical pretreatment of biomass at temperatures of 200-300 °C in an inert atmosphere and under atmospheric pressure [9-12]. The process aims to produce a solid fuel which possesses superior fuel properties compared to untreated biomass. Improvements after torrefaction include increased heating value, better grindability, and more hydrophobicity for torrefied biomass, which makes this fuel more readily suitable in subsequent conversion processes such as pyrolysis, liquefaction, gasification and combustion. Apart from the main solid product, the process also produces a number of by-products including water, carbon dioxide (CO_2), carbon monoxide (CO), and various organic compounds. They all are volatiles when

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formed at the torrefaction temperature. However, they can be classified into two groups: non-condensable and condensable volatiles. The former are permanent gases, while the latter becomes liquid after cooling to room temperature.

Recently, research and development activities on biomass torrefaction have been very active to look at torrefaction characteristics of a wide range of biomass species and to investigate the effects of the process parameters on the fuel properties of the torrefied products [13-18]. Although a number of torrefaction studies can be found in the literature, most of them focus on experimental approaches, from which information for up-scaling the process is limited. For example, process energy requirement is difficult to obtain from experiments, but it is essential for industrialization and commercialization of the process. Due to these reasons, torrefaction process has not been widely explored at industrial scale yet [19, 20]. Therefore, process modeling studies are needed to provide more information and to fulfil the current research gap between academia and industry. Only a few works for torrefaction process modeling can be found in the literature [21-25]. Haryadi et al. [21] and Dudgeon [22] provided simple torrefaction models to estimate the yield and the heating value of torrefied biomass. In another work, Nikolopoulos et al. [23] combined an Aspen Plus [26] model and chemical kinetics to study wheat straw torrefaction. However, no information about the energy consumption as well as the process energy efficiency can be found in these works. Bergman et al. [24] combined both experimental and modeling works in their report which investigated different torrefaction reactor technologies. The authors found that a direct-heated moving-bed reactor was an attractive option for torrefaction. A recent paper by Arteaga-Pérez et al. [25] on torrefaction of *Pinus radiata* and *Eucalyptus globulus* carried out energy and exergy analyses for the process. However, the authors ran simulations at

only two temperatures, which make it difficult to get an overview on the effect of temperature on the process energy consumption and optimization.

Being aware of the limitations of previous studies, this work aims to build a comprehensive torrefaction model using a commercial simulator. The model is capable of providing detailed distributions of the main torrefied products and by-products, from which the effects of torrefaction parameters on the products formation and properties can be obtained and compared with experimental data for validation. Moreover, overall energy consumption and process energy efficiency can be estimated and presented. More importantly, process optimization is also performed to investigate the optimal torrefaction operating conditions.

2 Methodology

This section explains in details the design of the torrefaction process used in this study, the role of all units, and the yield and energy calculations for the process.

2.1 Modeling and simulation

2.1.1 Model description

The flow diagram of the torrefaction model is illustrated in Figure 1. The model mainly consists of a drier, a torrefier, a combustor and several heat exchangers. A description and the role of each unit are presented in the next sub-sections, whereas general simulative conditions are summarized in Table 1.

2.1.1.1 Drier

A drier (DRIER) using air as drying agent is employed to reduce the moisture content of the feedstock (from 50 wt% to 10 wt%, wet basis) prior to torrefaction. Air at ambient temperature (stream DRY-AIR) is heated by the heat exchanger HX-AIRDR, and then the hot air (stream HOT-AIR) is connected to the DRIER for feedstock drying. After going through DRIER, outlet

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air stream is named as EXHAUST. In order to not affect the chemical properties of the feedstock during drying, the temperature of the HOT-AIR stream should not exceed 180 °C. On the other hand, a temperature high enough should be applied for the outlet streams to avoid water re-condensation on the dried biomass. Hence, an outlet temperature of 110 °C is chosen for the streams EXHAUST and DRY-BIOM. Moreover, the heat exchanger HX-EXH is used to utilize the heat from the stream EXHAUST to partially cover the heat for the stream DRY-AIR. The total heat required for drying (Q-DRY) is calculated as:

$$Q\text{-}DRY = QAIRDRY - Q\text{-}EXH + QL\text{-}DRY \tag{1}$$

where QAIRDRY is the heat required to heat the DRY-AIR stream, Q-EXH is the heat collected from cooling the EXHAUST stream, and QL-DRY is the heat loss during the drying process.

2.1.1.2   Torrefier

Torrefier is the main reactor in this model, where the biomass feedstock is thermally treated to produce torrefied biomass and by-products. Due to the complexity of torrefaction, it is difficult to use a pre-defined reactor in Aspen Plus to model this process. Consequently, it normally requires several blocks and calculators with FORTRAN codes to simulate this reactor [23, 25]. In this study, a user-defined hierarchy reactor (TOREFIER) is therefore used to represent the torrefaction reactor. The reactor TOREFIER requires two inlet streams: DRY-BIOM and N2-COLD. The stream DRY-BIOM is the outlet stream containing dried biomass from the previous DRIER, while N2-COLD is a nitrogen stream used as an inert agent for the torrefaction. The outlets of TOREFIER are TOR-BIOM and BYPROD, which stand for the torrefied biomass and by-products streams, respectively. The heat requirement for TOREFIER (Q-TOR) is calculated as:

$$Q\text{-}TOR = QBIOMHT + QN2HEAT + Q\text{-}WSPLT + Q\text{-}REACT + QL\text{-}TOR \qquad (2)$$

where QBIOMHT and QN2HEAT are respectively the heat required to heat biomass and nitrogen to the torrefaction temperature, Q-WSPLT is the heat needed to remove the remaining moisture in biomass, Q-REACT is the heat of torrefaction reaction, and QL-TOR is the heat loss during torrefaction.

2.1.1.3 Combustor and utilities

Because torrefaction by-products contain some combustible components, a combustor (COMBSTOR) is introduced to burn these species (from the stream BYPROD). An air stream (COMB-AIR) is employed as the oxidation agent. An excess air ratio of 1.3 is chosen in order to ensure a completed combustion. Thereafter, the hot flue gas stream (HOT-FG) from the combustor can be cooled via the heat exchanger HX-FG, thus the heat in the hot flue gas (Q-FG) can be utilized. On the other hand, the outlet stream TOR-BIOM contains hot torrefied biomass and needs cooling down via the heat exchanger HX-COOL, from which the heat (Q-COOL) can also be extracted. The stream PROD is the final torrefied biomass that can be stored for further applications. The heat collected from HX-FG and HX-COOL after subtraction of heat loss (QL-UTL) is utilized heat (Q-UTL) which can be used to partially balance the heat sinks throughout the process. Calculation of Q-UTL is given as:

$$Q\text{-}UTL = Q\text{-}FG + QCOOL - QL\text{-}UTL \qquad (3)$$

2.1.1.4 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 [27].

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- The properties method is Redlich-Kwong-Soave (RKS) [25].

- 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 total heat exchanged in the different blocks.
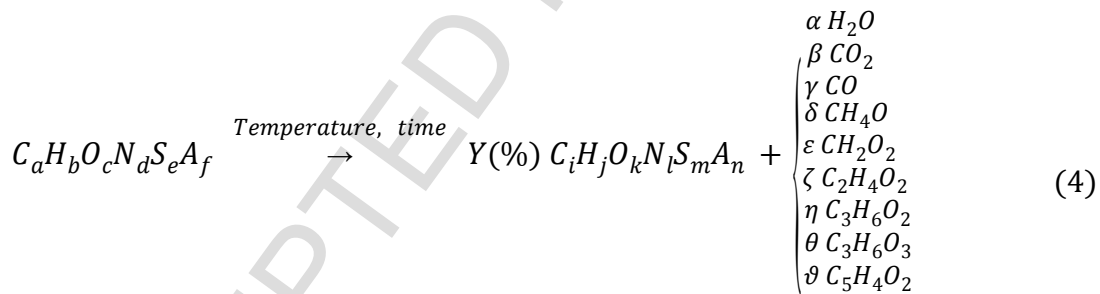
2.2   Modeling of torrefaction reaction

To date, the detailed reaction mechanism of biomass torrefaction has not been fully explored. It may be due to the fact that biomass components (including hemicellulose, cellulose and lignin) are complex and heterogeneous polymers whose thermal degradation reactions comprise many reactions and produce a number of products. Hence, identification of all torrefaction reactions and products is challenging. Apart from the torrefied biomass as main product, Prins et al. [16] analyzed the volatiles produced during torrefaction by High Performance Liquid Chromatography (HPLC) and showed that the volatiles include water, carbon dioxide, carbon monoxide, formic acid, methanol, lactic acid, furfural, hydroxy acetone and other trace organic compounds.

Recently, a two consecutive-reaction model has been employed to calculate the solid mass loss during torrefaction based on data collected from thermogravimetric analysis (TGA) experiments [15, 16, 28, 29]. In short, this torrefaction kinetic model assumes that raw biomass is converted to an intermediate solid and volatiles in the first reaction. After that, the intermediate solid continues

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reacting to form final solid and additional volatiles in the second reaction. The model was first used to study the kinetics of each reaction [15]. Later studies employed the model to calculate the evolution of both the solid and volatile products [28] as well as to predict the elemental composition of the solid products [29]. A combination of torrefaction models from previous studies was adapted in this work to model torrefaction reactions, shown in Eq. 4, which provides the yield and composition of the main solid product as well as the distribution of the by-products while varying torrefaction temperature and time.

If it is assumed that biomass contains only carbon, hydrogen, oxygen, nitrogen, sulfur and ash; then a general chemical formula for biomass can be written as $C_aH_bO_cN_dS_eA_f$ (where C, H, O, N, and S represent the elements and A denotes ash in biomass, subscript letters are calculated from the ultimate analysis of the fuel). Consequently, a torrefaction reaction for any temperature and time can be given, in Eq. (4):

$$C_aH_bO_cN_dS_eA_f \xrightarrow{Temperature,\ time} Y(\%)\ C_iH_jO_kN_lS_mA_n + \begin{cases} \alpha\ H_2O \\ \beta\ CO_2 \\ \gamma\ CO \\ \delta\ CH_4O \\ \varepsilon\ CH_2O_2 \\ \zeta\ C_2H_4O_2 \\ \eta\ C_3H_6O_2 \\ \theta\ C_3H_6O_3 \\ \vartheta\ C_5H_4O_2 \end{cases} \tag{4}$$

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.

However, it is worth noting that the model for volatile evolution was based on torrefaction of willow, a hardwood; and therefore are applicable only for other deciduous woods and may not for

coniferous species. This is because hardwood and softwood have different chemical compositions, which leads to different torrefaction behaviors and products distributions [29]. Due to these reasons, Norway birch, a hardwood, was chosen as the feedstock in this study. Available data for the fuel properties of Norway birch branches (Norwegian forest residues) are adopted from another work [30] 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.

2.3   *Calculations of torrefaction and energy efficiencies*

The key indicators of a torrefaction process are the mass and energy yields. They reveal how much dry mass is lost during torrefaction and how much energy is retained in the solid product. The definitions of these indicators are shown in Eqs. (5)–(7):

$$Y_M(\%) = \frac{m_{tor}}{m_{raw}} \times 100\% \tag{5}$$

where Y_M is the mass yield, m_{tor} and m_{raw} denote the mass of torrefied and raw biomass on dry basis, respectively.

$$D_E = \frac{HHV_{tor}}{HHV_{raw}} \tag{6}$$

$$Y_E(\%) = Y_M \times D_E \tag{7}$$

where D_E and Y_E are energy densification and energy yield; HHV_{tor} and HHV_{raw} respectively denote the higher heating values (HHV) of torrefied and raw biomass on dry basis.

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A very important factor for a process is its overall energy efficiency, which is normally used to evaluate the proficiency of a process in term of using energy. It should be noted that the process energy efficiency is different from the torrefaction energy yield in Eq. (7). The former can quantify how efficient the utilization of torrefaction gases proceeds and how much energy that is charged to the process through utilities [24]. On the other hand, the latter indicates how much energy from raw biomass is transferred into torrefied biomass after the pretreatment. Bergman et al. [24] defined the process energy efficiency (η_P) on the basis of lower heating value (LHV) in Eq. (8)

$$\eta_P = \frac{F_{prod}.LHV_{prod}}{F_{feed}.LHV_{feed} + E} \tag{8}$$

where F_{prod} and F_{feed} are the mass flow rate of the solid product and the feedstock, LHV_{prod} and LHV_{feed} are the lower heating values of the solid product and the feedstock on dry basis, E is the total energy required for sustaining the whole process.

3   Results and discussion

This section presents and discusses the results obtained from the aforementioned torrefaction model. In addition, model validation and process optimization are also included.

3.1   *Torrefaction products distribution and characterizations*

3.1.1   *Yields and fuel properties of torrefied biomass*

It is worth noting that different feed flow rates were applied in the Aspen Plus simulation in order to have the same energy content (based on LHV) in the torrefied biomass, which is chosen as 400kW. The simulation was carried out at different torrefaction temperatures, from 240 °C to

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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.

Simulation results for the mass and energy yields as well as the heating values of the torrefied biomass at different temperatures are presented in Figure 2. It can be seen from the figure that both the mass and energy yields of the torrefied biomass decrease while their heating values increase with increasing the torrefaction temperature. In details, when the temperature increases from 240 °C 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 MJ/kg to 24.8 MJ/kg. The main reason for increased heating value of torrefied biomass is changes in their elemental composition, which is illustrated in Figure 3 for the main elements including carbon, oxygen and hydrogen. Compared with the untreated biomass, whose carbon, oxygen and hydrogen contents are respectively 48.2%, 44.8%, and 6.2%; these values are 51.0-62.6% for carbon, 42.0-30.9% for oxygen and 6.1-5.2% for hydrogen after torrefaction. Moreover, the figure reveals that torrefaction temperature increases the carbon content while decreases the oxygen and hydrogen contents. The changes in the elemental composition of the torrefied biomass consequently lead to its increased heating value. These results are in good agreement with data available in the literature, which show decreasing trends for mass and energy yields and increasing trend for the heating value of torrefied biomass with increasing torrefaction severity [9-12].

3.1.2 *Distribution of torrefaction by-products*

Figure 4 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

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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). The dominances of water and carbon dioxide over other components are resulted from the dehydration and decarboxylation during torrefaction, which is well-documented in the literature [31].

3.1.3 Model validation

In order to validate the model, experimental data from other independent studies have been adopted for comparison. These works used birch [32] or a mixture of birch and other hardwoods [33] as feedstocks. A comparison of two main torrefaction indicators, mass yield and heating value, between the simulation data in this study and experimental results from [32, 33] is presented in Figure 5. It can be seen from the figure that the mass yield predicted in this study is higher than that obtained from experiments. A difference up to 11.1% can be found at the torrefaction temperature of 240 °C. On the other hand, the heating values from the experimental studies are close to that from the simulations with a largest deviation of 4.3%, found at the torrefaction temperature of 270 °C. Although there are some differences between the simulations and experiments, which may be due to differences in biomass species, growth locations and types of reactor, the general trends for both the mass yield and heating value are similar. Hence, these variations are relatively small and acceptable for engineering applications.

3.2 Heat required/produced and thermal energy efficiency

Detailed 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.

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Once can see from the table that higher feedstock flow rate is required when the torrefaction temperature is increased, which is due to the increased mass loss caused by the higher torrefaction temperature. For example, a flow rate of 162.0 kg/h is needed for torrefaction at 240 °C, while 192.7 kg/h is required for torrefaction at 300 °C. Consequently, the drying energy is increased from 81.8 kW to 97.2 kW due to the increased feedstock flow rate. Translating into percentage, drying accounts for 76-80% 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 [34-36]. The table also reveals that sustaining the torrefaction process requires only 20-24% of the heat required for the whole process, i.e., 20.0-30.5 kW, depending on the torrefaction temperature: the higher the torrefaction temperature is the more heat is required. Another important information is the utilized energy, which is from 21.0 kW at a torrefaction temperature of 240 °C to 99.4 kW at a torrefaction temperature of 300 °C. More energy collected from the utilities at higher torrefaction temperature is because more by-products are produced and combusted, i.e. more heat is produced. In addition, more heat is extracted at HX-COOL at higher temperature. Furthermore, Table 3 also exposes a decreasing trend in the thermal energy efficiency of the process, from 92.4% to 89.5%, when increasing the torrefaction temperature, which is due to increased heat loss with increasing temperatures (Table 3).

3.3 Process optimization

Recently, a few researchers tried to optimize torrefaction processes by several methods [37-40]. Chen et al. [37], who studied torrefaction of microalga residue (*C. vulgaris* ESP-31), showed that the optimal torrefaction operation depends on the requirement of energy densification of the fuel. Chin et al. [38] carried out a surface response analysis to examine experimental data from torrefaction of some biomass species. The authors developed a model for optimizing torrefaction,

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from which a balance between maximum HHV and minimum weight loss were achieved. A similar work by Lee et al. [39] also reported that the optimal torrefaction conditions can produce high energy density fuel. It can be seen that the aforementioned studies favored torrefaction at high severity in order to achieve high HHV of the torrefied biomass, or in other words, high energy densification and high energy density fuel. However, these conditions are coupled with more mass loss or lower mass yield. In addition, results in the present study show that higher torrefaction severity leads to more heat loss and consequently lower energy efficiency (Table 3). Therefore, an optimal torrefaction condition can be a trade-off between mass yield and HHV or energy densification of the torrefied biomass. Lee et al. [40] reported a Gain and Loss method for torrefaction optimization. The authors investigated the weight loss and heating value gain after torrefaction of seven biomass materials. The two factors were normalized in order to obtain comparable data sets. The optimal torrefaction condition was defined as the intersection of two curves (i.e., weight loss and heating value gain). A similar approach is adopted in the present study: three important torrefaction factors including mass yield and HHV of torrefied biomass as well as process energy efficiency obtained from the simulation are normalized according to Eq. 9.

$$z_i = \frac{x_i - min\,(x)}{max\,(x) - min\,(x)} \tag{9}$$

where z_i and x_i are the ith normalized and original values, $min\,(x)$ and $max\,(x)$ are the minimum and maximum of the original values.

Because the mass yield and the energy efficiency reduce when the torrefaction temperature increases while the HHV shows an opposite trend, the normalized mass yield versus the normalized HHV and the normalized energy efficiency versus the normalized HHV are plotted and presented in Figure 6, from which the intersection between the mass yield and the HHV is

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about 275 °C, while that between the energy efficiency and the HHV is approximately 278 °C. Therefore, it can be concluded that a temperature in the range of 275-278 °C is optimal for a torrefaction time of 30 min for birch branches, where trade-off points between the HHV and the mass yield or the energy efficiency can be achieved.

4   Conclusions

A completed torrefaction model has been built in the Aspen Plus v8.8 software and validated by independent experimental data. Norwegian forest residue (birch branches) was chosen as the feedstock. The model is capable of providing the distributions of both the torrefied biomass and by-products. Simulation results show good agreement with available experimental 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. Trends for carbon, oxygen and hydrogen contents are consistent with other experimental works. The model also reveals that drying accounts for 76-80% of the total heat demand. Moreover, the process energy efficiency reduces with increasing torrefaction temperature, thus torrefaction at high temperatures is not recommended. In addition, process optimization shows that a temperature of 275-278 °C is optimal for a torrefaction time of 30 min for birch branches.

5   Acknowledgement

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Table 1. General conditions for the Aspen Plus simulations

Conditions	Unit	Values
Drier		
Moisture in	wt%	50
Moisture out	wt%	10
Inlet air temperature	°C	180
Outlet air temperature	°C	110
Torrefier		
Temperature	°C	240-300
Residence time	min	30
Combustor		
Excess air ratio		1.3
Product cooler		
Product outlet temperature	°C	50

Table 2. Fuel properties of feedstock

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

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

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

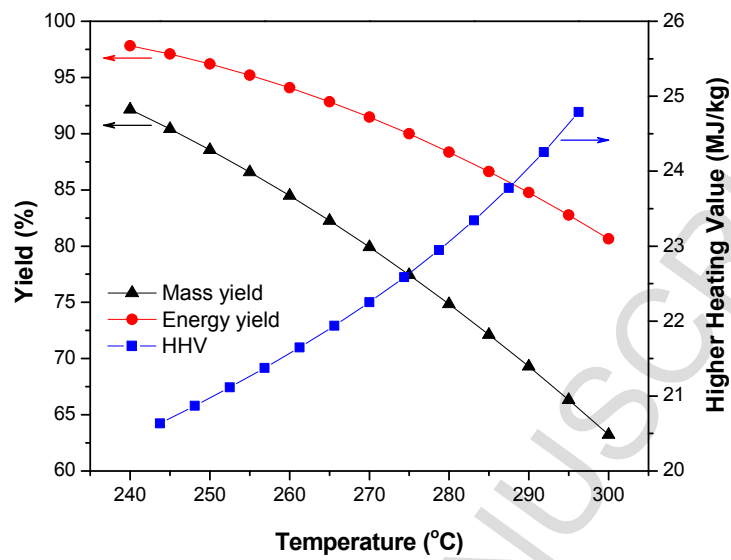|		Torrefaction temperature						
		240°C	250°C	260°C	270°C	280°C	290°C	300°C
Feedstock flow rate	kg/h	162.03	164.38	167.65	171.93	177.39	184.22	192.72
Product flow rate	kg/h	74.66	72.79	70.82	68.70	66.39	63.82	60.93
Drying heat	kW	-81.80	-82.99	-84.64	-86.80	-89.55	-92.99	-97.27
Torrefaction heat	kW	-20.00	-21.09	-22.40	-23.95	-25.78	-27.93	-30.49
Utilized heat	kW	20.95	27.31	35.88	46.93	60.83	78.08	99.38
Heat loss	kW	-11.58	-12.50	-13.72	-15.28	-17.24	-19.67	-22.66
Energy efficiency	%	92.42	92.21	91.89	91.48	90.95	90.30	89.49

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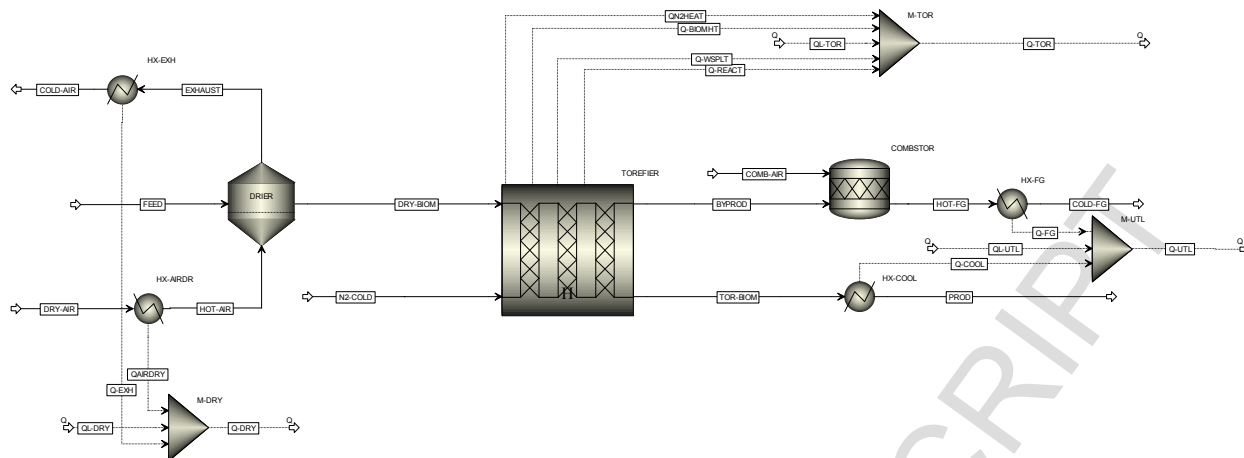
Figure 1. Flow diagram of the torrefaction model

Figure 2. Plots of mass yield, energy yield and heating value of torrefied biomass at different
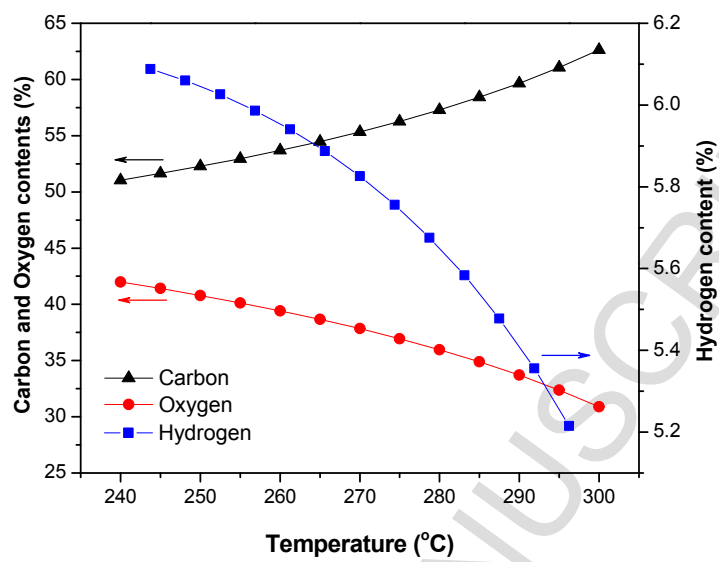
temperatures

Figure 3. Effect of torrefaction temperature on main elements in torrefied biomass
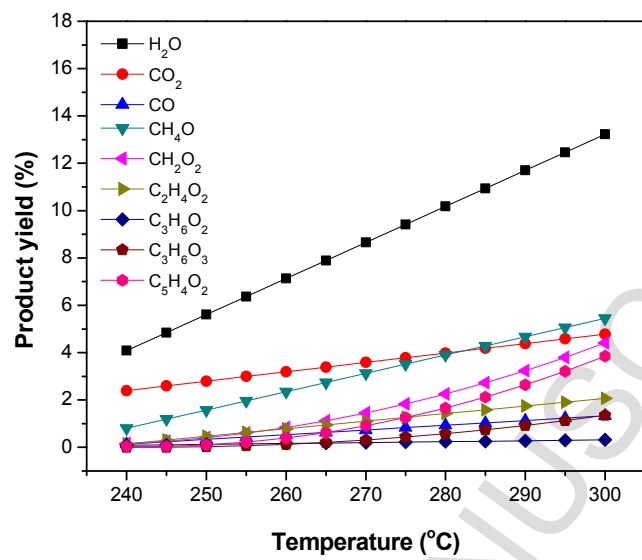
Figure 4. Distribution of torrefaction by-products at different temperatures
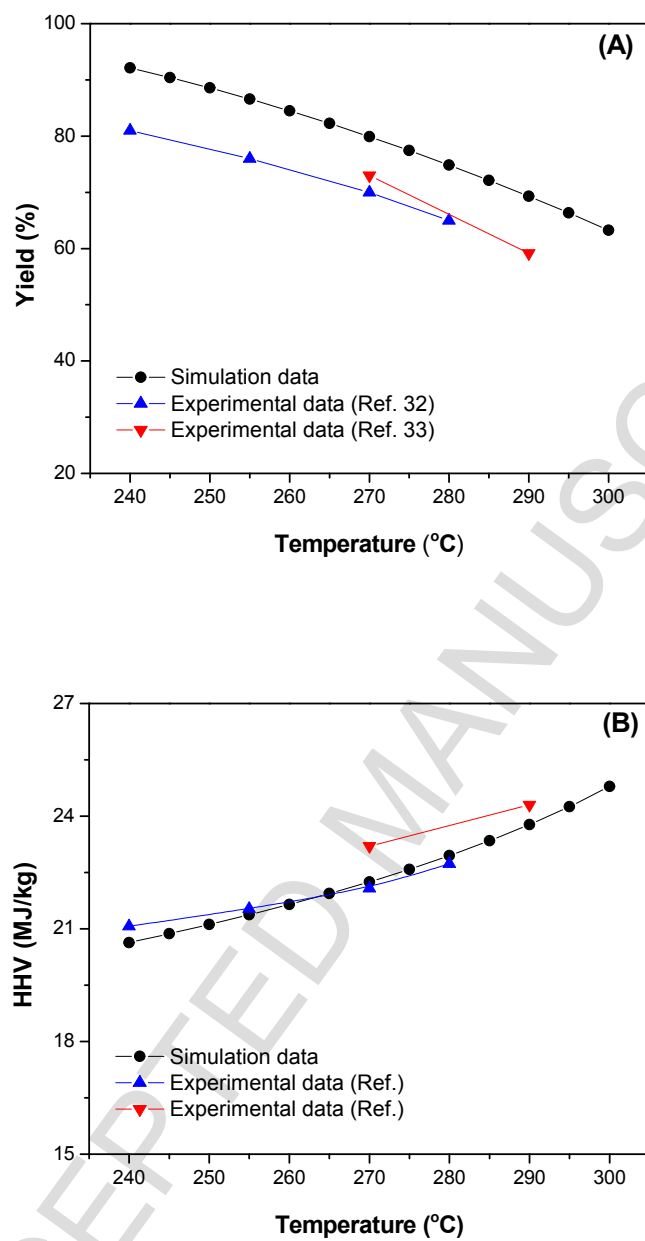
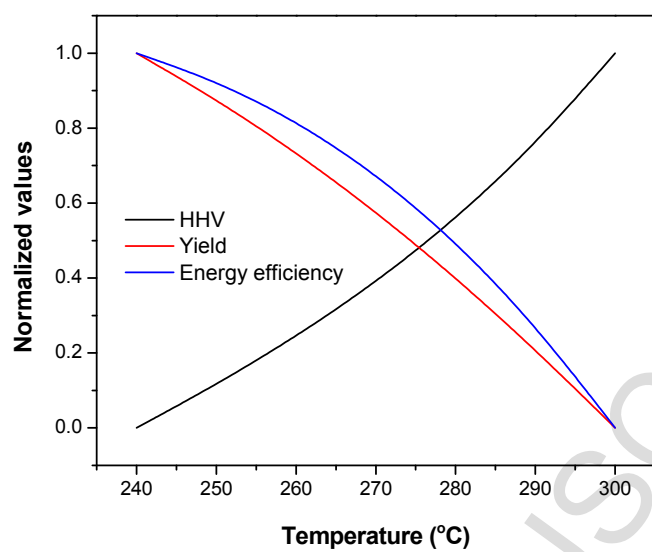Figure 5. Model validation for (A) mass yield and (B) HHV

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Figure 6. Plot of normalized values for HHV, mass yield and energy efficiency

Highlights

- Completed torrefaction model has been built in the Aspen Plus and validated by experimental data.

- The model is capable of providing the distributions of both the torrefied biomass and by-products.

- The model also reveals that drying accounts for 76-80% of the total heat demand.

- Process optimization shows that a temperature of 275-278 °C is optimal for a torrefaction time of 30 min for birch branches