Assessment of the energetic efficiency of a continuously operating plant for hydrothermal carbonisation of biomass

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Abstract: To date wet lignocellulosic biomass cannot be used efficiently for energy production. By hydrothermal carbonisation (HTC) wet biomass may be efficiently transformed to a solid, lignite-like fuel with good dewatering and grinding properties and a high calorific value. Energetic yields of the HTC reaction can be derived from lab scale experiments. However, for the assessment of energetic efficiencies of a HTC plant the amount of external energy consumption needs to be calculated. A model of a semi-continuously HTC plant is presented with a heat recovery system which is based on recycling of hot compressed water. Results of simulations with the program Engineering Equations Solver show that energy consumption can be significantly reduced by internal heat recovery. Efficiencies of a HTC plant model are presented based on experiments with beech wood chips as a model biomass. A sensitivity analysis of the water content of the biomass and the heat of reaction is presented.

Keywords: *Hydrothermal carbonisation, biomass, heat recovery, efficiency*

1. Introduction

Hydrothermal carbonisation (HTC) is a pretreatment process of biomass in hot compressed water at around 200°C. Thereby the carbon content and higher heating value (HHV) is increased[1,2]. Apart from application as a soil ameliorant it therefore has been discussed as fuel[3]. The product (related to as “hydrochar” or “char”) leaves the reactor as a slurry and must be mechanically dewatered and dried for combustion. By removing water and further compression an energetically dense fuel can be formed facilitating transportation and storage. Good grinding properties make it applicable for gasification and further refining. Energetic yields of the solid of 75-90 % for the HTC process with regards to the HHV can be expected, because the whole fraction of lignocellulose is converted. The HHV of the solid increases when higher temperatures are applied. Yet, the energetic yield decreases for higher temperatures because of a decrease of the solid yield[2,3,4]. Potential feedstock includes digestate, municipal waste, grass, leaves, bagasse and wood[5]. Mass and energetic yields in this contribution are derived from lab scale and pilot scale experiments.

However, in order to assess the energetic efficiency of a HTC plant also external energy consumption must be taken into account - especially for heating the biomass to reaction temperature, for mechanical dewatering of the hydrochar slurry and for drying. The amount of energy needed to heat biomass with a water content of 80% to reaction temperature is app. 24% of the energy of the hydrochar. For drying of char with a water content of 30% app. 4% of its energy is needed. This shows that external energy consumption may decrease the efficiency of a HTC plant significantly and that heat recovery within an elaborated heat regime is crucial. In prior works it was shown that the use of flash steam from expansion of the hot slurry can significantly increase the efficiency of the process[6,7]. But release of pressure and the mixing of steam with colder water necessarily results in a loss of exergy, compared to direct recycling of hot compressed water which is proposed here.

1.1. Semi-continuous biomass feeding

Generally batch or continuous systems are applicable for a HTC plant. Yet, for continuous or semi-continuous systems, reaction heat can be used more efficiently. Also adjacent equipment can be utilized more efficiently and pressure changes in the reactor can be avoided. However, feed systems for solid matter against pressure are challenging – especially for heterogeneous biomass. Piston pumps usually can only pump biomass with a water content of 90%. For dry matter lock hopper systems are widely used, although they come along with a loss of gas for every cycle. Yet for the case of HTC this does not necessarily need to be a disadvantage because reaction gas needs to be discharged from a continuous reactor. Lock hopper valves are prone to abrasion and plugging. Here ball segment valves with a nominal diameter of up to 600 mm made of ceramic may be appropriate[8]. In order to reduce the loss of gas, further feeding systems have been developed including rotary feeders, plug-forming feeders, non-plug-forming feeders[9]. In this contribution we will present a model of a semi-continuously operating system with a lock-hopper feeding system.

1.2. Heat recovery

For a HTC plant an efficient processing of heat will be crucial. In a continuous HTC plant there are three mechanisms which require most of the energy and which are addressed by the plant model: (1) Much water along with the biomass needs to be heated to reaction temperature. This can be reduced if relatively dry biomass is fed via a lock hopper system. Additional water to fully cover biomass in the reactor and enhancing the reaction may be hot compressed process water which is recycled. However this requires mechanical dewatering of the hydrochar slurry after the reaction at elevated temperature and pressure. (2) Additional energy is used for drying wet hydrochar, which requires that the product is mechanically dewatered as well as possible. By dewatering at reaction temperature, a significantly lower water content can be expected. This is because of lower surface tension, density and viscosity of hot water, as was practically examined and realized for mechanical-thermal dewatering of lignite[10,11]. (3) By discharging reaction gas from the reactor a significant amount of steam is discharged as well. By increasing the absolute pressure in the reactor and hence the partial pressure of reaction gases, the loss of vapour can be decreased.

The model aims at using only internal heat sources for preheating of biomass and for drying. Only for the highest temperature level before the entrance of biomass in the reactor external energy is used for the supply of steam.

2. Modelling

For the simulation the program Engineering Equation Solver (EES) is used. Mass and enthalpy balances were entered for all mass flows. Enthalpy of components (except for steam) is set to zero for 0°C. The process is modelled in a steady state although lock hopper and piston press work semi-continuously in reality. Indirect heat transfer to solids or slurries is difficult and fouling on heat exchangers may increase considerably above 100°C[7]. Therefore in the model it is assumed that indirect heat transfer is only feasible up to a temperature of 100°C. The model assumes a capacity of the plant of 2000 kg/h of dry biomass. Below the model is described in detail and is depicted in Fig. 1.

2.1. Preheating of biomass

Biomass with a water content of 0.6 is heated by indirect heat transfer by low temperature waste water and vapour to 100°C at atmospheric pressure. The heat capacity of dry biomass and hydrochar is 1.6 $kJ/kg{\cdot}K^{-1}$ and 1.45 $kJ/\ kg{\cdot}K^{-1}$ respectively. After preheating at atmospheric pressure biomass is fed to the lock hopper and is mixed with internal steam from the first flash tank. Then it is mixed with hot compressed water and is finally mixed with external steam from a steam generator until it reaches the necessary temperature and water to biomass ratio of 7:1. External steam is produced by a steam generator operated with natural gas with an efficiency of 0.9.

2.2. HTC reaction

The heat of reaction was measured by differential scanning calorimetry (PerkinElmer DSC-7). 4 mg of ground poplar wood were heated with 20 mg of de-ionized water to 220°C in stainless steel high pressure capsules. In the reference capsules only de-ionized water was used. The experiments were conducted according to ISO 11357-1:1997 and ISO 11357-5:1999. In [12] the applicability and uncertainty of this method for long lasting heat flows is discussed in detail. The mean heat released by the reaction within the first 4 hours was 500 J/g of dry biomass. The uncertainty of the experiments was 30% but could be higher if process water was recycled and therefore in the sensitivity analysis it is altered from 200 to 800 J/g.

In the model the biomass enters the reactor where it reaches the reaction temperature of 210°C by heat of reaction. Heat equilibration is assumed to be dominated by evaporation of water at superheated areas at the bottom of the reactor and condensation at relatively cold biomass on the top. Heat losses of the reactor were assessed to be 5-20 kW depending on insulation which accounts for 0.2% of the system power of the HTC plant. This shows that heat losses in an industrial scale may play a minor role which is not the case for lab experiments which require constant heating in order to maintain a certain temperature. In the model an overall heat loss of 20 kW is assumed and is completely attributed to the reactor.

The model uses experimental mass and energy balances of the HTC reaction. Solid yield, gas yield and heating values are derived from lab experiments with beech wood chips in a 200 mL reactor which could also be reproduced in a 250 L pilot scale reactor. The experiments were performed at the same conditions which are assumed in the model (reaction temperature 210°C, reaction time 4h, water to biomass ratio 7:1). The main results of the experiments which are used in the model are depicted in Table 1.

Table 1. Mass and energy balances of lab and pilot scale experiments with uncertainties shown in parenthesis.

	$wood_{dry}$	$char_{dry}$	solid yield	gas	gas yield	HHV	LHV	energetic $yield_{HHV}$
	mass(g)	mass(g)	(-)	mass(g)	(-)	(MJ/kg)	(MJ/kg)	(-)
Lab scale	19.98 (0.03)	12.88 (0.09)	0.644 (0.003)	0.69 (0.01)	0.035 (0.001)	23.27	22.01	0.781[1]
Pilot scale	14710 (120)	9980 (860)	0.680 (0.064)	-		22.88	21.53	0.808[1]

[1] HHV_{wood} =19.20 MJ/kg, LHV_{wood}=18.06 MJ/kg

Mass and energy yields could be well reproduced for lab experiments. Mass yields from pilot scale experiments altered mainly because the reactor could not be flushed as well. Solid and energetic yields are slightly lower and HHV is slightly higher than reported earlier for experiments at similar temperatures[3,4]. This can be explained by application of higher water to biomass ratio and longer reaction time in the experiments presented above, which will be discussed in detail elsewhere.

The ratio of reaction water and solved organic substances to biomass is 0.32 according to the experiments, yet in the model thermodynamic properties of pure water are assumed. It is assumed that reaction gas only consists of carbon dioxide. The partial pressure of the reaction gas in the reactor is assumed to be 0.9 MPa in order to be completely removed by gas loss of the lock hopper.

2.3. Mechanical dewatering and drying:

Electricity consumption of the piston press is calculated in two steps. First the char is dewatered to a water content of 0.6 with a pressure of 3 MPa. Then the char is dewatered to a final water content of 0.3 by a pressure of 10 MPa. The work is calculated by multiplying the volume of the displaced water with the respective pressure and assuming an efficiency of 0.9. The primary energy consumption of the piston press PEC_{press} is calculated by multiplying the electricity consumption with a primary energy factor. A factor of 2.5 is applied assuming an energy conversion efficiency of the char of 40% in a thermal power plant and thus resulting in a primary energy consumption of the piston press of 0.163 GJ/h.

The water content of the hydrochar after mechanical dewatering is assumed to be 30% corresponding to 31% achieved by pilot scale mechanical-thermal dewatering of lignite at 200°C[10,11]. After dewatering the pressure of the piston is released. In the model it is assumed that this results in evaporation of residual water and cooling to 105°C. Further assuming adiabatic conditions this results in drying to 22% water content which compares to 24% achieved at 200°C[10,11]. Relaxation steam is used for preheating biomass. Afterwards biomass is dried in a rotary drier using steam at 130°C from the second flash tank and abstracted reaction gas and steam from the reactor. Values for desorption heat of lignite[10] are used for the simulation of drying and no external energy is used for drying.

The efficiency of the plant in Table 2&3 is calculated according to Eq. (1):

$$efficiency_{HHV/LHV} = \frac{energy_{hydrochar,HHV/LHV}}{energy_{biomass,HHV/LHV} + energy_{natural\ gas} + PEC_{press}} \qquad (1)$$

3. Results

3.1. Simulation results

In Fig. 1 the model as presented before is depicted including mass flows and state variables. The biomass is heated by steam from the first flash tank to 156°C and then is mixed with the hot compressed water from the piston press.

This way the slurry reaches 196°C and only a limited amount of external heat is needed to finally heat biomass and water to 205°C. The amount of external energy needed for this step is 1.03 GJ/h which is 2.7% of the energy of the biomass and 3.4% of the energy of the hydrochar. Heat of reaction then is sufficient to heat biomass to reaction temperature of 210° and to make up for heat losses and gas losses via the lock hopper. The temperature of the waste water is 105°C and cannot be further used at this temperature level. The char can be dried to a water content of 7% by using only internal heat.

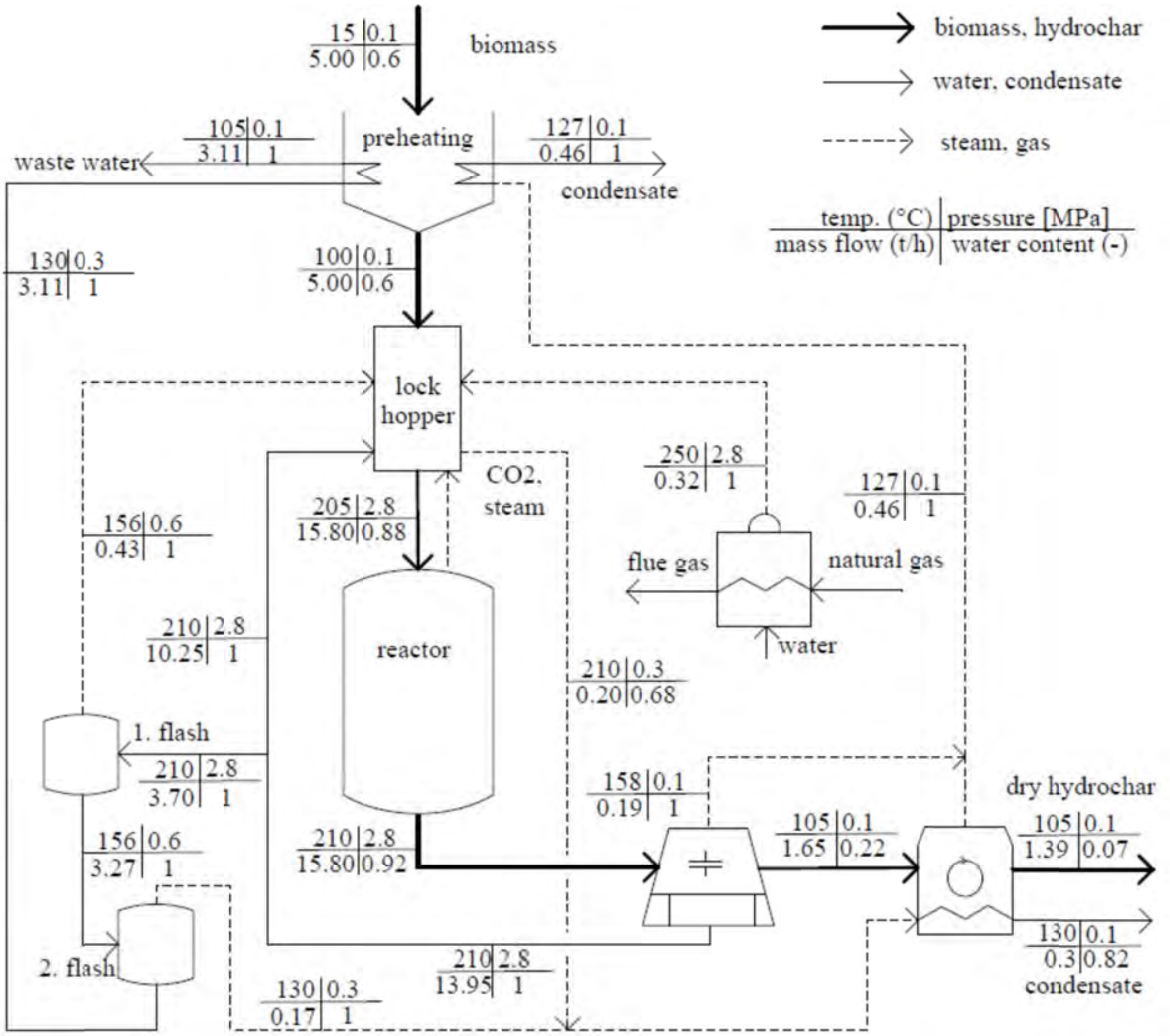

Fig. 1. Model of HTC plant with mass flows and state variables.

3.2. Sensitivity analysis

The water content of the biomass significantly determines the amount of energy needed to heat the biomass to reaction temperature. Therefore it was varied as an input parameter in the simulation from 0.5-0.75 and results are depicted in Table 2. For a higher water content the amount of natural gas needed increases and makes up between 2.2 % and 7.3 % of the energy of the hydrochar. On the other hand the water content of the dried char decreases significantly. This is because less water can be recycled allowing for a higher amount of steam from the second flash tank to be used for drying. The efficiency is calculated both on basis of the HHV and LHV. The efficiency of the HTC plant decreases with a rising water content on the basis of the HHV because more external energy is required. The efficiency of the plant increases on a LHV basis because the lower heating value of the biomass decreases significantly with a higher water content.

Table 2. Results from the variation of the water content of biomass.

water content		energy (GJ/h)					efficiency	
biomass (-)	char (-)	natural gas	biomass (HHV)	biomass (LHV)	char (HHV)	char (LHV)	(HHV) (-)	(LHV) (-)
0.5	0.104	0.650	38.40	31.24	30.06	28.07	0.767	0.876
0.55	0.088	0.819	38.40	30.16	30.06	28.13	0.763	0.903
0.6	0.069	1.032	38.40	28.80	30.06	28.20	0.759	0.940
0.65	0.044	1.307	38.40	27.06	30.06	28.29	0.754	0.992
0.7	0.011	1.675	38.40	24.73	30.06	28.40	0.747	1.069
0.75	0.000	2.191	38.40	21.47	30.06	28.43	0.738	1.193

For a very wet feedstock it may be favourable to mechanically dewater biomass before feeding it to the HTC plant. This would drastically decrease the amount of waste water by recycling a larger part of the water. Therefore it would also decrease the amount of energy needed to heat biomass to reaction temperature. Assuming a decrease of water content of 0.15 in a screw extruder and an electricity demand of 50 kWh/t_{DM}[13] and a primary energy factor of electricity of 2.5 the energetic breakeven point would be at a water content of 0.71 of the biomass.

The heat of reaction was varied in the model between 200 and 800 J/g while the water content of the biomass is set constant to 0.6. The results are depicted in Table 3. With increasing heat of reaction the amount of natural gas needed decreases significantly and would be zero for 840 J/g for the heat of reaction. As less external heat is consumed for heating the biomass, slightly more internal water is recycled. Therefore, less internal steam is available for drying the char, resulting in a small increase of the water content.

Table 3. Results from variation of reaction heat.

reaction heat (J/g)	water content char (-)	energy (GJ/h) natural gas	efficiency (-) (HHV)	(LHV)
200	0.054	1.946	0.742	0.914
300	0.059	1.641	0.748	0.923
400	0.064	1.336	0.754	0.931
500	0.069	1.032	0.759	0.940
600	0.074	0.728	0.765	0.949
700	0.078	0.425	0.771	0.958
800	0.083	0.122	0.777	0.968

In the past it was disputed if a self sustaining heat regime was achievable for a HTC plant. As shown above heat demand both depends on the water content of the biomass and the heat of reaction. This means that at a certain water content the heat of reaction would have to be above a certain value. Eq. (2) describes the cases in which the condition of a self sustaining heat regime would be fulfilled for the configuration presented above:

$$h_{reac} \geq 245 * e^{2.1*WC} \qquad (2)$$

where h_{reac} is the heat of reaction (J/g) and WC is the water content (-).

4. Discussion & Conclusion:

It is shown that external energy consumption of a HTC plant can be significantly reduced by addressing the most energy consuming processes of biomass preheating, char drying and reaction gas abstraction. By recycling of hot compressed water efficient heat recovery can be achieved. By using internal heat only, biomass can be heated to 196°C and hydrochar can be dried to 7% water content. External primary energy is needed to further heat biomass to reaction temperature. Electricity is consumed for mechanical dewatering of the char. The total amount of external primary energy for the base case is 4% of the energy of the char which is about half as much as calculated earlier[6]. Depending on the amount of water content and heat of reaction it varies between 1-8%.

Efficiencies for the HHV of the presented HTC plant range from 74-78% based on lab experiments with beech wood chips. Further studies on energetic yields of the HTC reaction are necessary for different feedstock and reaction conditions. However, it can be assumed that external primary energy consumption mainly depends on the plant set up and on the water content of the biomass and the heat of reaction.

In previous publications the intensity of the heat of reaction was overestimated considerably by theoretical considerations. Here values from calorimetric measurements are used and it is shown that it is an important parameter for the assessment of the efficiency of a HTC plant. Therefore additional research is necessary for a better understanding of this parameter.

Recycling of process water is favourable because the amount of waste water can be reduced and heat can be recovered. It is shown that mechanical dewatering of biomass before the HTC reaction can reduce primary energy consumption for wet biomass. In addition a higher amount of recycled water may also slightly increase the energetic yield of the hydrochar because parts of the organic substances in the water may polymerize further. For quantification of this effect further studies are necessary which require extensive dewatering of samples after reaction. Also by further decreasing the ratio of water to biomass the solid yield can be increased. Both effects may increase the solid yield by a few percent.

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