

ENERGY FROM BIOMASS FOR CONVERSION OF BIOMASS

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Along with estimates of minimum energy required by steam explosion pre-treatment of biomass some general problems concerning biomass conversion into chemicals, materials, and fuels are discussed. The energy necessary for processing biomass by steam explosion auto-hydrolysis is compared with the heat content of wood and calculated in terms of the amount of saturated steam consumed per unit mass of the dry content of wood biomass. The fraction of processed biomass available for conversion after steam explosion pre-treatment is presented as function of the amount of steam consumed per unit mass of the dry content of wood.

The estimates based on a simple model of energy flows show the energy required by steam explosion pre-treatment of biomass being within 10% of the heat content of biomass – a realistic amount demonstrating that energy for the process can be supplied from a reasonable proportion of biomass used as the source of energy for steam explosion pre-treatment.

1. INTRODUCTION

The stocks of non-renewable world resources being used up require considering more efficient and rational consumption of what is left and to look for renewable substitutes of feedstock supply for products essential to support the civilization. A practical solution of problems posed by transfer from non-renewable fossil feedstock and energy sources for industries to renewable inputs provided by photosynthesis is seen as transformation of the existing petrochemical refineries into bio-refineries. According to the concept elaborated by the Laboratory of Biomass Eco-Efficient Conversion of the Latvian State Institute of Wood Chemistry [1–3] bio-refinery is a cluster of integrated technologies converting biomass into transportation fuels, power, chemicals, and advanced materials within the zero emissions framework. Bio-refineries are assumed to combine technologies necessary to transform the biological raw material into industrial intermediates and final products [4]. By combining processing technologies the mixed biomass feedstock is converted into a variety of products. The bio-refinery concept is based on ideas common to approaches of green chemistry [1] and is an equivalent of that for petroleum refineries producing fuels and multiple products from fossil oil.

The steam explosion (SE) auto-hydrolysis technology is a promising pre-treatment for further conversion of biomass into different kinds of products. The value of SE auto-hydrolysis as a pre-treatment technology to convert biomass into

a number of products lies in its potential application for production of second- and third-generation bio-fuels, and advanced composite materials from residues and waste. It can serve as the kernel of any of the integrated clusters of technologies to produce fine chemicals, paper, building materials, food, pharmaceuticals, fuels, etc. and a complement to farming and bioengineering [3].

Since the energy required to obtain any final product is expected to become a crucial factor of making choices between technological solutions in the age of strongly limited flows from renewable resources, assessments of energy consumption by any proposed technological process are important and should be of interest. The total amount of available biomass being the source for both the energy and materials requires having an idea of the proportion necessary to supply the energy needed for processing. The simple model of energy flows at SE auto-hydrolysis considered earlier [5] is further used to make tentative estimates of the proportion of biomass necessary to be used as the source of energy for steam explosion auto-hydrolysis pre-treatment of biomass.

2. THE PHYSICAL MODEL AND MATHEMATICAL EXPRESSIONS

The SE auto-hydrolysis (steam explosion, steam explosion pulping, steam cracking) is a simple technique [6] by which biomass is subject to action of saturated steam at pressures up to 4 MPa. After being held at high pressure during the time of some seconds to some minutes the biomass is decompressed (exploded) to ambient pressure. Empirically, the result may be determined by a single parameter being a function of exposure time and temperature [7]. However, other factors such as moisture content of the sample, particle size, etc. as well have some effect on the result.

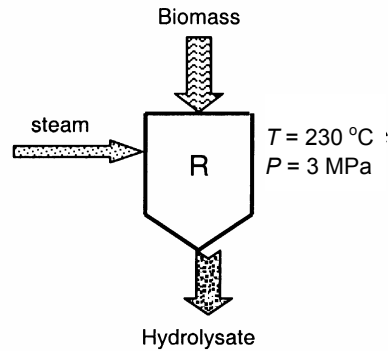


Fig. 1. Diagram of steam explosion model used for calculations.

The model (Fig. 1) used to calculate the cost of SE treatment in terms of energy [5] showed essential dependence of the energy consumption on the moisture content of the biomass being processed. The effect can be assessed by some critical limit of moisture content M_c at which the energy spent on heating the waterless part of the biomass to the required temperature is equal to the energy spent on raising the temperature of the moisture:

$$M_c = \frac{C_b(\Delta T)}{C_b(\Delta T) + (\Delta h)m_w} = 0.5, \quad (1)$$

where: C_b – the specific heat of dry biomass;

ΔT – the difference between the operation temperature and the initial temperature;

Δh – the enthalpy difference of water content of the biomass with respect to ΔT ;

m_w – the mass of moisture content

Energy E actually consumed to heat the biomass up to the required operation temperature is more than the calculated amount of energy

$$E_o = C_b(\Delta T) + m_w(\Delta h) \quad (2)$$

and depends on efficiency F of the system:

$$E = \frac{E_o}{F} \quad (3)$$

Assuming that E_o is the amount of calculated necessary energy per unit biomass and E – the amount of energy actually consumed per unit biomass at processing by steam explosion the number of biomass units N that can be processed at the expense of using a unit biomass to supply the energy for processing is a linear function of efficiency of the system:

$$N = \frac{E_c}{E} = \frac{F}{\frac{E_o}{E_c}} \quad (4)$$

where E_c is the combustion energy of biomass,

The coefficient determining the slope of the linear function $N(F)$ is the maximum possible number of biomass units processed consuming the energy released at burning unit biomass (Fig. 2).

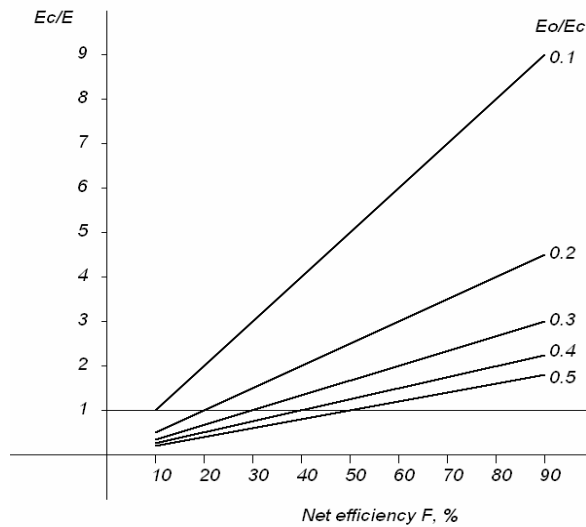


Fig. 2. The number of mass units of the dry content of biomass processed by steam explosion at the expense of consuming the heat content of unit biomass E_c depending on the amount of energy E spent per unit mass of the dry content is equal to the ratio E_o/E and dependent on the net efficiency F of the system. The ratio of energy E_o from Eq. (2) to E_c determines the maximum calculated number of dry biomass units processed by energy E_c .

Under conditions that the energy for processing is obtained using a part of the same kind of available biomass as fuel, the fraction Y of biomass available for treatment and further utilization (the yield) is calculated from

$$Y = \frac{1}{1 + \frac{E}{E_c}}. \quad (5)$$

The general pattern of the relationship between the fraction of biomass available for use and efficiency of energy consumption given by Eq. (5) is illustrated in Fig. 3.

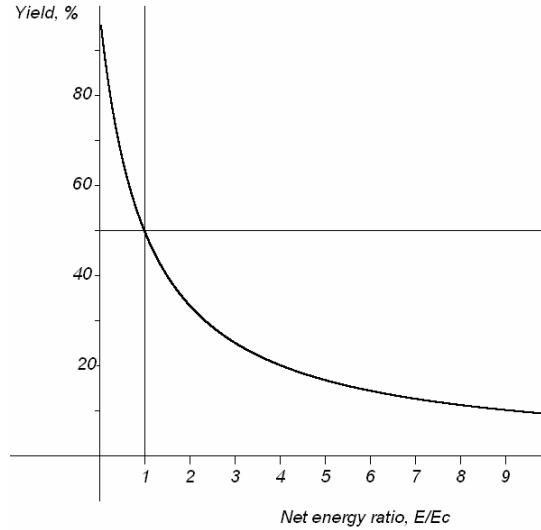


Fig. 3. Proportion of biomass available for treatment (yield) as function of energy consumed per unit mass of the dry content expressed in terms of combustion energy (heat content) E_c of biomass in the case the same kind of biomass is used as the source of energy for the process. The line at $E/E_c = 1$ corresponds to the conditions that one half of the available amount of biomass is consumed to supply the energy for processing the other half.

The energy for biomass treatment by steam explosion being supplied by saturated steam at the operation temperature can be expressed in terms of the amount of steam consumed per unit mass of the processed dry organic substance. Assuming that biomass is heated at the expense of energy released at condensation of saturated steam at the operation temperature, the mass of condensed saturated steam m_{cs} is found from the equation:

$$m_{cs} E_{evap} = E_o, \quad (6)$$

where: E_{evap} is the heat of evaporation at the operation temperature;
 E_o is given by Eq. (2).

The total amount of saturated steam necessary for the process is found as the sum of the amount of steam being condensed to heat the biomass and the amount of steam m_o necessary to maintain the pressure in the reactor:

$$m_o = \frac{V}{v}, \quad (7)$$

where: V – the volume of the reactor occupied by the biomass containing one mass unit of the dry substance to be treated,
 v – the specific volume of saturated steam under operation pressure and temperature.

The energy to generate the total amount of steam $m_s = m_{cs} + m_o$ is:

$$E_s = m_s \cdot (\Delta h), \quad (8)$$

where from the maximum efficiency of energy use at steam explosion F_{SE} is found from Eq. (3) as the ratio:

$$F_{SE} = \frac{E_o}{E_s}. \quad (9)$$

3. RESULTS AND DISCUSSION

The moisture content of wood being defined as the ratio of moisture mass m_w to the sum of the mass content of water and dry biomass m_w : $(m_w + m_b)$, the critical moisture content from Eq. (1) is of the order of the moisture of air-dry wood, which means that energy consumed to dry the biomass before processing by steam explosion must be taken into account in the total energy balance of the process.

From thermodynamic tables of saturated steam [8] the values of enthalpy difference Δh ($2720.3 \text{ kJ kg}^{-1}$), evaporation energy E_{evap} ($2258 \text{ kJ} \cdot \text{kg}^{-1}$) and specific volume v ($66.7 \text{ cm}^3 \text{g}^{-1}$) of saturated steam at pressure of 3 MPa are found. With the data of specific heat C_b ($1.76 \text{ kJ} \cdot \text{kg}^{-1} \text{K}^{-1}$) [9-11] and combustion energy of biomass E_c (14.5 MJkg^{-1}) [11] the energy E_o from Eq. (2) is found to be 810 kJ per kg of the dry content of wood at 14% moisture wherefrom the amount of steam condensed to heat the biomass from Eq. (6) is equal to 0.360 kg. Assuming that 1 kg of biomass would fit loosely within a volume of 5 litres, the mass of steam m_o from Eq. (7) is found to be equal to 0.075 kg, the total amount of steam thus being 0.435 kg. According to Eq. (8), generating that amount of saturated steam at 230 °C would require at least 1180 kJ of energy, comprising about 8% of the biomass combustion energy.

The yield of processed biomass (under conditions that steam is generated by burning the same kind of biomass) as function of steam consumed per 1 kg dry biomass is shown in Fig. 4.

The ultimate efficiency of energy consumption by SE processing of biomass estimated from Eq. (9) under the conditions considered is equal to 68 % and grows with the growth of moisture content. A better indicator of the efficiency is the ratio of energy (E_b) consumed per unit dry biomass against the energy required to generate the necessary amount of steam, which is about 30–34% at 6–14% moisture decreasing with the moisture content. Any further processing of the steam-exploded biomass requires spending some additional energy for decreasing the amount of biomass available for conversion into useful products if the energy is supplied by using the same kind of biomass as fuel.

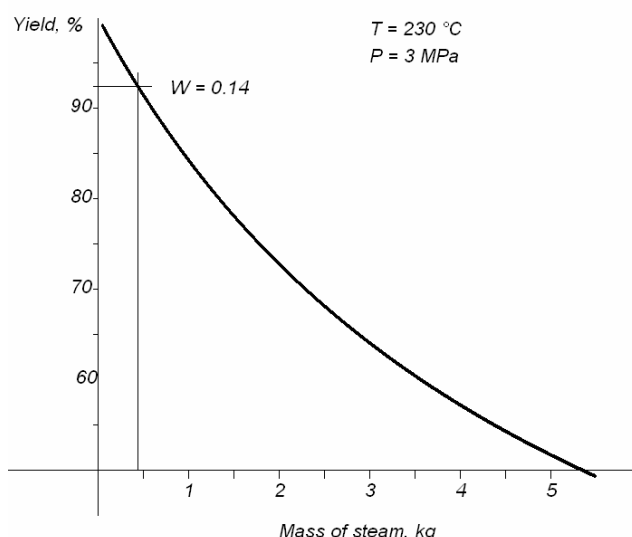


Fig. 4. Proportion of available biomass processed by SE (yield) at the expense of using the rest to generate steam as function of the amount of steam consumed per unit mass of the dry content. The steam consumption minimum and utmost yield calculated for moisture content of 14% are shown. Only the part of the yield vs. steam curve exceeding 50% is presented.

Since the fraction of solar energy fixed by photosynthesis in the net product is much smaller than that reradiated into space or accumulated as hydro-potential or wind [12], the use of biomass as fuel is justified only with regard to waste that cannot serve as source for valuable products.

Steam explosion is an appropriate technique helping to solve the problem of separating lignin from lignocelluloses to produce bio-ethanol from cellulose and hemicelluloses instead of food crops. However, there is not enough of the source material to satisfy a growing demand for energy, food, chemicals, and materials. The same considerations are true concerning another advanced technique for production of bio-fuels – the consolidated bio processing [13]. Recent estimates of cellulosic feedstock products in USA available for making bio-fuels [14] show that it can satisfy only 50% of the country's present demand.

The question of whether the products of photosynthesis might satisfy the energy demand by the global economic system requires a more detailed consideration. A rough estimate shows that the energy presently consumed by the global economic activities of civilization is of the same order of magnitude as the net product of photosynthesis – between 15 and 20%. It is not clear what kind of consequences we should expect if additional 20% of photosynthesis is going under control and use by the humans.

Efficiency of using the available land is another factor of importance considering production of bio-fuels. Even the most optimistic assumption of capturing 0.5% of solar radiation in biomass by photosynthesis is 40 times less than catching the energy of solar radiation from the same area by photovoltaic panels at 20% efficiency. For that reason producing bio-fuels from special crops does not make sense from the point of energetic efficiency of land use. Technologies of bio-fuel production should focus on agricultural by-products or waste instead.

Moreover, the estimates accounting for the price in terms of energy of bio-ethanol produced from corn [15] reveal a rather small return to the amount of energy invested – a mere 1.5 units per unit under conditions that biomass residues are used as energy source of the process and credit is given to the distillers dried grain with soluble compounds used as forage. If residues are not used to substitute part of the energy source, only 0.65 units of energy are returned per unit energy invested, which means that in this case producing ethanol from corn requires more energy than the amount of energy the produced fuel can provide.

Producing bio-ethanol from sugar cane might show higher returns because of exploiting cheap labour instead of harvesting machinery that needs to be fuelled. As revealed by a recent report in “Der Spiegel” magazine [16] about labour conditions on the sugar cane plantations in Brazil, the grounds for a cheap final product of the ethanol distilleries is the extremely inadequate and, by the civilized Western standards, socially unacceptable reward for the hard work.

With a number of needs and demands for a limited annual net product of photosynthesis, priorities should be set with regard to its utilization and the land allocated for production where the hierarchical order starts with the source of food for humans and feedstock for animals and satisfying the need for materials before burning the scarce unique asset to release the energy stored in the products of photosynthesis.

4. CONCLUSIONS

Calculations of the essential amount of energy necessary for steam explosion processing as a pre-treatment for further separation of the main components of lignocellulosic biomass show the steam explosion being a sustainable technology in the sense that the required energy can be supplied from a reasonable proportion of the available biomass – less than 20% of the heat content of biomass at 50% efficiency. The calculated amount of steam consumed per unit dry content of biomass at operation temperatures up to 230 °C is within the limits of 1 kg under the circumstances.

As far as the capacity of photosynthesis is limited by natural conditions, priorities need to be set for rational use of land and the net product sustaining the planet's biosphere.

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BIOMASAS ENERĢIJA BIOMASAS KONVERSIJAI

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Kopsavilkums

Apstrādājot lignocelulozes biomasu ar tvaika sprādziena auto-hidrolīzes paņēmieni, var viegli atdalīt tās komponentus tālākai konversijai, iegūstot ķīmiskās izejvielas, materiālus un degvielas. Izmantojot vienkāršu tvaika sprādziena enerģijas patēriņa modeli, novērtēts šim procesam nepieciešamās enerģijas daudzums uz absolūti sausas apstrādātās masas vienību salīdzinājumā ar biomasas (koksnes) siltumspēju. Aplēses rāda, ka apstrādei nepieciešamās enerģijas daudzums pie reaktora darba temperatūrām līdz 230 °C nepārsniedz 10% no biomasas siltumspējas, bet piesātināta tvaika patēriņš – vienu kg uz kilogramu sausā biomasas satura pie 50% enerģijas izmantošanas efektivitātes. Tālākai izmantošanai pieejamās apstrādātās biomasas proporcija parādīta kā funkcija no enerģijas (3. att.) un tvaika (4. att.) patēriņa pie nosacījuma, ka daļa no kopējās biomasas daudzuma izmantota kā enerģijas avots procesam.

Balstoties uz datiem par fotosintēzes produktos uzkrāto Saules starojuma enerģijas daļu, autori izvirza apsvērumus par zemes izmantošanas un bioenerģētikas efektivitāti. Izsīkstot neatjaunojošos fosilo resursu krājumiem, fotosintēzes produktu izmantošanā prioritāte jāpiešķir pieprasījumam pēc izejvielām ķīmiskajai rūpniecībai un materiāliem, atstājot nišu otrās un trešās paaudzes biodeģijai.

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