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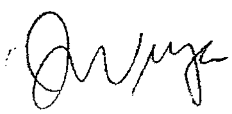
Checked/Approved/Issued by:  H.J. Veringa		ECN Biomass

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TORREFACTION FOR BIOMASS UPGRADING

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ABSTRACT: Torrefaction is a mild pre-treatment of biomass at a temperature between 200-300 °C. During torrefaction the biomass its properties are changed to obtain a much better fuel quality for combustion and gasification applications. In combination with pelletisation, torrefaction also aids the logistic issues that exist for untreated biomass. This paper treats the principles of torrefaction and production technology that is under development at ECN (TOP technology for the production of TOP pellets from biomass). Attention is also paid to the process its economics and its influence on the economics of a biomass-to-energy production chain. Torrefaction of biomass is an effective method to improve the grindability of biomass to enable more efficient co-firing in existing power stations or entrained-flow gasification for the production of chemicals and transportation fuels. Torrefaction by means of the TOP process leads to a very energy dense fuel pellet of 15-18.5 GJ/m^3. Typically, the process has a thermal efficiency of 96% and the total production costs amount 40-50 €/ton of TOP pellets. The logistic costs amount 50%-66% the costs involved with wood pellets.
Keywords: Pre-treatment, Torrefaction, TOP Technology, TOP pellets, logistics

1 INTRODUCTION

Biomass is an important energy source to create a more sustainable society. However, nature has created a large diversity of biomass, not to forget the modifications men makes to biomass to use it in industrial or domestic applications. Hence the composition and properties of biomass is subjected to many natural and human factors. Some of these need to be improved seriously to enable their application as sustainable fuel in highly efficient biomass-to-energy chains. This can be achieved through torrefaction.

Biomass torrefaction is a pre-treatment method carried out at 200-300 °C in absence of oxygen. The occurring decomposition reactions at this temperature level cause the biomass to become completely dried and to loose its tenacious and fibrous structure. Therewith the grindability of the subjected biomass is improved significantly. In addition, torrefaction increases the calorific value and the biomass its hygroscopic nature can be destructed to yield a hydrophobic material. Depending on the applied torrefaction conditions, torrefied biomass is coloured brown to dark-brown and approaches the properties of coal.

These changes make torrefied biomass very attractive for combustion and gasification applications. Moreover, besides the thermal conversion of biomass also logistic properties can be improved through torrefaction when torrefaction is combined with densification (pelletisation). By this combination very energy dense fuel pellets are produced.

The application of torrefaction as a new pre-treatment technology is only interesting when it leads to a reduction of costs of the overall biomass-to-energy production chain. Especially when considering that torrefaction technology yet has not reached a commercial status. At ECN, the research and development on torrefaction is fully dedicated to achieve this goal. In the last 3½ years, this has resulted in the generation of mechanistic knowledge and design data for optimal reactor and (integral) process design. This paper discusses some of the interesting outcomes, with attention paid to torrefaction principles, feedstock requirements, product applications, production technology and economy of torrefaction. This is done with focus on production technology in development at ECN.

2 TORREFACTION PRINCIPLES

Torrefaction is a thermo-chemical treatment method that is earmarked by an operating temperature ranging from 200 °C to 300 °C. It is carried out at near atmospheric pressure in the absence of oxygen and characterised by low particle heating rates (< 50 °C/min). The biomass partly decomposes during the process giving off various types of volatiles, which results in a loss of mass and chemical energy to the gas phase.

The yield of mass and energy from the original biomass to the torrefied biomass is strongly dependent on torrefaction temperature, reaction time, and biomass type. Typical values are a mass and energy yield of 0.8 and 0.9 respectively (LHV_{daf}). Hence, in torrefaction more mass than energy is lost to the gas phase. This phenomenon results in energy densification (higher LHV_{daf}). On 'as received' basis' the mass and energy yields can be even 0.45 and 0.9 respectively (35% moisture content).

In general (woody and herbaceous) biomass consists of three main polymeric structures: cellulose hemicellulose and lignin. Together these are called lignocellulose. For each polymer similar reaction regimes can be defined, but they proceed at different temperature levels [4]. Hemicellulose is most reactive and is subjected to limited devolatilisation and carbonisation below 250 °C. Above 250 °C it is subjected to extensive devolatilisation and carbonisation. Cellulose is most thermo-stable and is subjected to limited devolatilisation and carbonisation only. Lignin its reactive is in between both others.

Loss of the tenacious nature of the biomass is mainly coupled to the breakdown of hemicellulose matrix, which bonds the cellulose fibres in biomass [3]. Depolymerisation of cellulose decreases the length of the fibres.

Bergman *et. al.* [1] classified the main reaction products of torrefaction, as is applied to Table I, which shows a mass and energy distribution of willow torrefaction. The mass and energy from the biomass is predominantly preserved in the solid product (torrefied biomass). The relative high mass yield of (reaction) water is remarkable and it is produced from the dehydration of all polymers. Most of the (chemical) energy lost from the solid product is in form of organics and lipids (see [1] for more details).

Table I: *Mass and energy distribution for torrefaction of willow and 280 °C and 17.5 min reaction time [1]*

Reaction products	Mass yield (daf) (%)	Energy yield (LHV, daf) (%)
Solid	87.5	94.9
Lipids	1.40	3.40
Organics	1.70	1.60
Gases	1.40	0.10
Water	8.00	0.00

In torrefaction biomass loses relatively more oxygen and hydrogen compared to carbon. Water from dehydration is the best example, but also all organic reaction products (acetic acid, furans, methanol) and gases (mostly CO_2 and CO) contain a considerable amount of oxygen. An increase of the calorific is the main result from this. Depending on the torrefaction conditions, the LHV_{dry} of biomass can be increased from 17-19 MJ/kg to 19 to 23 MJ/kg.

Biomass is completely dried during torrefaction and after torrefaction the uptake of moisture is very limited. Depending on the torrefaction conditions this varies from 1 to 6% on weight basis. Hence, the hygroscopic nature of biomass is at least partly lost, which is contributed to the destruction of OH-groups through dehydration. This prevents the formation of hydrogen bonding. In addition, the biomass is also subjected to chemical transformations with little mass loss. In these rearrangement reactions unsaturated structures are formed which are non-polar [5,6]. It is likely that this property is also the main reason that torrefied biomass is practically preserved so that biological degradation does not occur anymore.

The volumetric density changes due to the deep drying causing the biomass to shrink. This process is comparable to drying of biomass. The mass loss during torrefaction causes the biomass to become more porous and hence results in a decrease of the volumetric density. Densities of 180-300 kg/m^3 were observed [1]. Densification of torrefied wood is very well possible through pelletisation. Probably due a higher content of lignin and fatty unsaturated structures in torrefied biomass, high density pellets of 750-850 kg/m^3 can be produced from torrefied biomass [2].

3 FEEDSTOCK REQUIREMENTS

Torrefied biomass can be produced from a big variety of biomass while yielding similar product properties. The main reason for this is that about all biomass are built from the same polymers (lignocellulose). The chemical changes of these polymers during torrefaction are practically similar resulting in the same property changes. However, at same operating conditions, mass and energy yields will vary for different biomass, as the polymeric composition and reactivity may differ. This was observed for torrefaction of beech, willow, straw and larch [3]. Consequently, each biomass will have its own set of operating conditions (recipe) to achieve the same product quality.

The mass and energy yield may also differ as a result of differences in the extractives or lipids between different biomass. Some biomass such as grass contains more waxes than for instance wood. Lipids and extractives are believed not to be involved in torrefaction decomposition reactions, but are driven off the biomass by evaporation.

Torrefaction is rather a slow process, requiring rather long residence time of 5 to 15 min. The influence of particle size is therefore not as strong as is known for flash-pyrolysis for instance. In general typical woodchips about 2 cm thickness can be torrefied without heat transfer limitations [3]. This may however be dependent on the heat transfer characteristics of the used torrefaction reactor.

4 PRODUCT APPLICATIONS

The superior fuel quality of torrefied biomass makes it very attractive for combustion and gasification applications in general. Their thermal efficiencies can be improved due to the high calorific value. However, pulverised fuel combustion in coal-fired power stations and entrained flow gasification are in particular interesting product outlets. In both applications biomass has to be fed to the reactor as a powder, which is difficult and costly and is only at very low capacity achievable in classical coal-mills. Because of this, wood pellets are currently the state-of-the art for co-firing (in the Netherlands), as these consist of sufficiently small particles. However, wood pellets are very costly and still require serious modifications to the existing coal-infrastructure (from storage to burners in boiler).

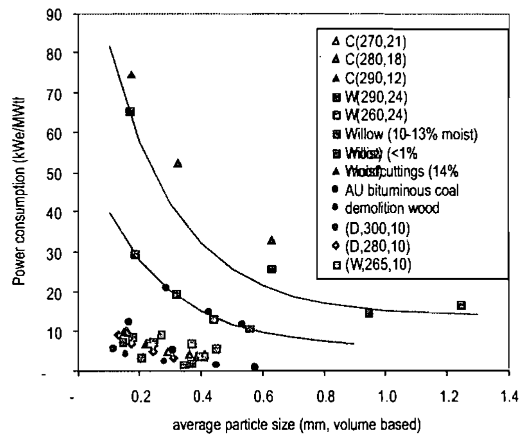

Figure 1: *Size reduction results of various torrefied biomass and feed biomass. Coding: Biomass(torrefaction temperature, reaction time), W=willow, C=woodcuttings, D=demolition wood. See [1,2,3] for more details*

Figure 1 provides results on the size reduction of torrefied biomass produced under different conditions, biomass and coal. A heavy duty cutting mill was used. It can be observed that the power consumption reduces dramatically when biomass is first torrefied. Depending on the applied torrefaction conditions, the reduction in power consumption ranges from 70% to 90%. A capacity increase of the mill of similar magnitude was observed [3]. Depending on the applied torrefaction conditions, the capacity increase is with a factor 7.5 to 15.

The most important phenomenon of Figure 1 is that torrefied biomass its size reduction characteristics show great similarity with coal.

Advantages of torrefied biomass are not only found in the final thermal conversion itself, but also in logistical aspects of the biomass-to-energy production chain. At ECN the development of the so-called TOP process (**To**rrefaction and **P**elletisation) is ongoing to bring TOP pellets to the energy market within the near future. These fuel pellets can have a bulk energy density in the range from 15 to 18.5 GJ/m^3. Wood pellets, which are known to be a very energy-dense biomass fuel, range from 8 to 11 GJ/m^3. Hence, TOP pellets can also be attractive for house-heating applications as is commonly applied in the Nordic countries, Austria and Germany. For the large-scale biomass import, which is relevant to areas with low biomass resources, transportation costs can be dramatically reduced.

5 PRODUCTION TECHNOLOGY

Torrefaction is considered to be a new development for biomass upgrading for biomass-to-energy production chains and is not commercially available yet. During the eighties of the last century a demonstration plant was built and operated by the company Pechiney (France), though this was for a different product application. This plant was dismantled in the beginning of the 1990's for economic reasons. Since the interest in torrefaction as a pre-treatment technology of biomass for combustion and gasification, new concepts for torrefaction have been proposed [7,8], but none have been developed to commercial status neither to the stage of technical demonstration.

State-of-the art technology would therefore be the Pechiney process with a 12,000 ton/a production capacity. The torrefied biomass was to be applied as a reduction agent for the production of aluminium. A scheme of this plant is given by Figure 2. The process consisted of its own feedstock preparation (chopping). The hearth of the process consisted of biomass drying, torrefaction (roaster) including product cooling, and combustion of the torrefaction gas (combustibles) to generate heat for drying. An indirectly heated (jacketed) screw reactor, normally used for drying, was deployed as torrefaction reactor. Heat was put in by means of circulating thermal oil that was heated in an individual boiler. The residence time of the reactor was 60-90 min.

Although this technology proofed to be technically feasible for torrefaction, it suffered from a low energy efficiency (60-80%) and the screw reactor has poor scale-up characteristics. The required capital investment of the demonstration plant was nearly 3 M€ and the total production costs over 100 €/ton product (±7 €/GJ). Scale up of the technology would be in form of parallel operated production lines, which possibly could reduce the production costs to about 75-80 €/ton product for a capacity of 230 kton/a (without feedstock costs) [1]. In many cases such economics will not lead to a attractive economics for the overall production biomass-to-energy production chain.

Therefore, the main objectives of the torrefaction projects carried out at ECN were to come to an energy efficient process with low production and logistical costs.

This has resulted in the TOP technology of which the torrefaction part is schematically depicted in Figure 3.

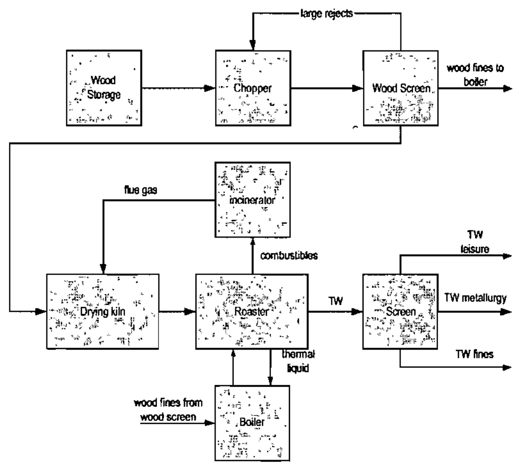

Figure 2: *Plant-layout of the Pechniney process*

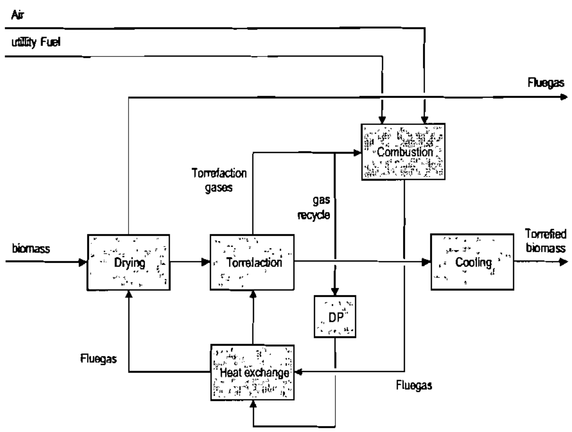

Figure 3: *Plant-layout of the ECN TOP technology [3]. Only the integrated drying-torrefaction part of the process is shown (not size reduction and pelletisation)*

In contrast to the indirectly heated pechniney process, the TOP process is based on direct heating of the biomass during torrefaction by means of hot gas that is recycled. The hot gas consists of the torrefaction gas itself and is re-pressurised and heated after each cycle. The necessary heat for torrefaction and pre-drying is produced by the combustion of the liberated torrefaction gas. Possibly a utility fuel is used when the energy content of the torrefaction gas is insufficient to thermally balance the torrefaction process. This process concept is recognised to be very promising for torrefaction. Use is made of a dedicated torrefaction reactor that is based on moving bed principles, but with unique features for optimal heating and temperature control with minimal pressure drop. It is optimised towards heat integration, and is suitable for free and non-free flowing biomass and waste. Currently, this reactor is under development at ECN. The typical commercial scale of operation is expected to be 60-100 kton/a of product, which is on energy basis comparable to the typical production scale of pelletisation (80-130 kton/a). Scale-up is in practice limited by scale-up characteristics of the drying unit.

The thermal efficiency of the TOP process is typically 96% on LHV basis (net process efficiency typically 92%) For a feedstock moisture content of 50%. Heat losses are mainly encountered in the drying of the biomass. This high efficiency can be achieved, as long as the torrefaction gas can be used as dryer fuel and does not contain more energy than needed. A decrease of efficiency will occur when the devolatilisation of the biomass during torrefaction is too severe. Therefore tuning of the energy content of the liberated torrefaction gas to the total heat demand of torrefaction and drying is crucial for obtaining a high energy effciency.

6 ECONOMICS TOP TECHNOLOGY

The total capital investment of the TOP technology is estimated to be 5.5 to 7.5 M€, depending on the size of the feedstock and for a capacity of 60 kton/a of product. The total production costs including depreciation and financing amount 40 to 50 €/ton TOP pellets [2].

A business case was developed to explore the economic advantages of TOP pellets over wood pellets [2]. The cost breakdown of this business case is given by Table II and is based on pellet production in South Africa and sales to power stations in the North-West of Europe.

Table II: *Cost-breakdown (in €/GJ) of pellet production in South-Africa and end-user application in NW-Europe*

	TOP Process	Pelletisation process
Feedstock	0.7	0.7
Pellet production	2.0	2.2
Logistics	1.8	2.9
Integral costs at delivery power station	**4.5**	**5.8**

A dramatic cost reduction can be observed due to a large reduction of the logistic costs particularly. This completely contributed to the high energy density of the TOP pellets, which results in large savings in especially sea transportation.

The current market price of wood pellets in the Netherlands is in between 6 to 7 €/GJ. With respect to the profitability of the production chain, TOP technology would lead to an increase of the internal rate of return from 12% (wood pellets) to ±30% for the pellet production and logistics part of the production chain. However, serious cost savings of 30-80% may also be expected at the power station itself mainly due to decreased investment costs in pellet storage and the required processing line to the boiler. In the case that TOP pellets are processed using an infrastructure that is required for wood pellets, cost savings of the power station may increase the internal rate of return from 12% to 25%. The power station makes even more profit when TOP pellets can be stored and processed together with coal.

7 CONCLUSIONS AND OUTLOOK

Torrefaction is a new technology to upgrade biomass for combustion and gasification applications. The product properties of torrefied biomass (TOP pellets) are superior over the biomass it is produced from. Still, the required technology that will make its introduction in biomass-to-energy chains economically justified is not yet mature.

TOP technology produces TOP pellets against attractive production costs. Dramatic cost savings can be achieved throughout the chain when compared to state-of-the art wood pellets. This justifies its further development. The technical demonstration of the technology is the next phase of development, which is planned in the near future.

Biomass is an important energy source to create a more sustainable society. Torrefaction aids nature to keep developing its wide diversity of biomass species. But when time is ready, it converts this diversity within a narrow range of fuel specifications. But at the end it starts to feed nature with green CO_2.

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