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(71) Applicant (for all designated States except US): **MORTIMER TECHNOLOGY HOLDINGS LIMITED** [GB/GB]; 92 New Greenham Park, Thatcham, Berkshire RG19 6HW (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **DODSON, Christopher** [GB/GB]; Mortimer Technology Holdings Limited, 92 New Greenham Park, Thatcham, Berkshire RG19 6HW (GB). **GROSZEK, Martin** [GB/GB]; Mortimer

Technology Holdings Limited, 92 New Greenham Park, Thatcham, Berkshire RG19 6HW (GB).

(74) Agents: **SETNA, Rohan, P.** et al; Boulton Wade Tennant, Verulam Gardens, 70 Gray's Inn Road, London WC1X 8BT (GB).

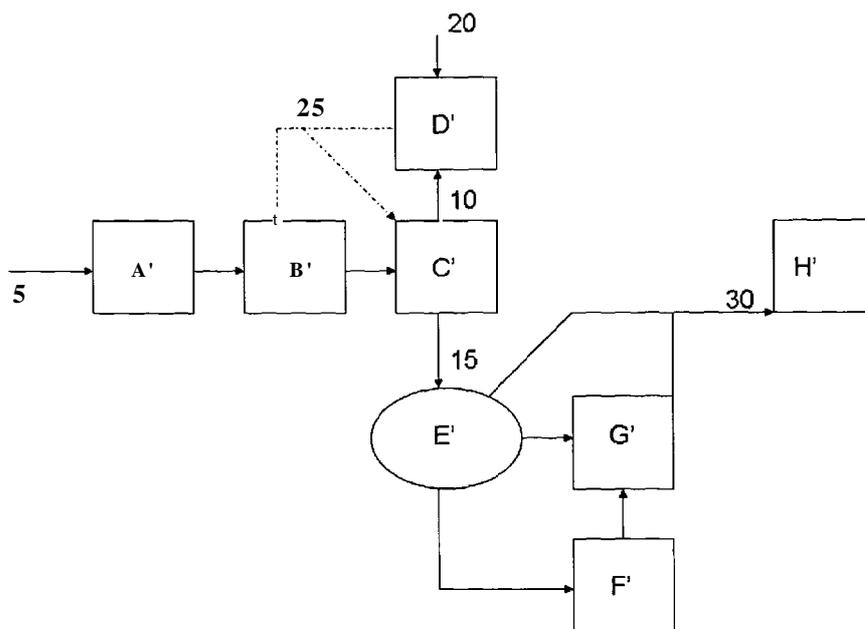
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[Continued on next page]

(54) Title: TORREFACTION PROCESS

Figure 2



(57) Abstract: The present invention relates to a process for the torrefaction of a biomass feedstock for the production of a biofuel, the process comprising: (i) torrefaction of a biomass feedstock in a toroidal bed reactor, wherein the toroidal bed reactor comprises a reaction chamber with a substantially circumferentially directed flow of fluid generated therein to cause the biomass feedstock to circulate rapidly about an axis of the reaction chamber in a toroidal band, and to heat the biomass feedstock, wherein the fluid comprises gas or gases introduced into the reaction chamber and wherein the chamber is maintained under an oxygen-depleted atmosphere.

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### Torrefaction Process

The present invention relates to a process for treating a biomaterial, for example, wood chippings to produce a biofuel. In particular, the present invention provides an improved  
5 torrefaction process. Furthermore, the present invention provides an improved fuel suitable for use in processes such as energy production.

Torrefaction is a thermo-chemical treatment of biomass generally at 200 to 320 °C. It can also be described as a mild form of pyrolysis. Pyrolysis occurs above 400°C. It is carried  
10 out under atmospheric conditions and in the absence of oxygen. During torrefaction the biomass properties are changed to obtain a much better fuel quality for combustion and gasification applications. For example, the water contained in the biomass as well as superfluous volatiles are removed, and the biopolymers (commonly cellulose, hemicellulose and lignin) partly decompose giving off various types of volatiles.

15 The final product of torrefaction is the remaining solid, dry, blackened material which is referred to as "torrefied biomass" or "bio-coal". In order to create highly efficient biomass-to-energy chains, torrefaction of biomass in combination with densification (pelletisation/ briquetting), can be used to overcome logistic economics in large scale green energy  
20 solutions. Torrefaction combined with densification leads to a very energy dense fuel carrier of 20-25 GJ/ton. Furthermore, this densification into pellets further increases the hydrophobic properties of the material making bulk storage in open air feasible.

Torrefied biomass can be produced from a wide variety of raw biomass feedstocks while  
25 yielding similar product properties. This is because of the lignocelluloses polymers present in all biomass. In general (woody and herbaceous) biomass consists of the above three main polymeric structures: cellulose, hemicelluloses and lignin.

During the process, the biomass loses typically 20% of its mass (dry weight basis), while  
30 only 10% of the energy content in the biomass is lost. This energy (the volatiles) can be used as a heating fuel for the torrefaction process. An additional benefit of torrefaction is that all biological activity in the product is eliminated, reducing the risk of fire and stopping biological decomposition.

Torrefaction of biomass leads to improved grindability of biomass. This leads to more efficient co-firing in existing coal fired power stations or entrained-flow gasification for the production of chemicals and transportation fuels.

5 Torrefaction processes have historically been long retention time processes. There is therefore a desire for an improved, preferably faster, process for treating a biomass, or at least a process that will mitigate some of the problems associated with the prior art or provide a useful alternative thereto. Furthermore, there is a desire for an improved or alternative fuel source.

10

Accordingly, in a first aspect, the present invention provides a process for the torrefaction of a biomass feedstock for the production of a biofuel, the process comprising:

(i) torrefaction of a biomass feedstock in a toroidal bed reactor,

wherein the toroidal bed reactor comprises a reaction chamber with a

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substantially circumferentially directed flow of fluid generated therein to cause the biomass feedstock to circulate rapidly about an axis of the reaction chamber in a toroidal band, and to heat the biomass feedstock, wherein the fluid comprises gas or gases introduced into the reaction chamber and wherein the chamber is maintained under an oxygen-depleted atmosphere.

20

According to a second aspect, the present invention provides a biofuel obtainable according to the process of the present invention.

25

The inventors have found that by using a toroidal bed reactor the process may be conducted in a significantly shorter time. That is, a toroidal bed reactor is ideal for the fast torrefaction of a biomass feedstock. Without wishing to be bound by theory, it is believed that the high turbulence in the reactor allows for express and more precise treatment of the feedstock through increased heat and mass transfer. This minimises undesirable oxygen contact which might lead to scorching. The ready throughput allowed  
30 by the reactor allows for a higher temperature to be used with even heating of the particles so that a surprisingly short residence time may be used.

The process of the present invention can provide an end product with a calorific value, greater than 20 GUmt. It is well know that conventional torrefaction process can also

achieve an end product with a calorific value of around 22 GJ/mt. However, the retention times required for this are long. For example:

1. Fluidized beds : 12-20 minutes
2. Plug flow kilns, screws: 30 minutes-2 hours

In contrast, example retention times and the consequent calorific values of the product produced by using a toroidal bed reactor in accordance with the present invention are set out in Table 1 below.

10

Table 1

	Temperature [°C]	Residence time (sec)	LHV (GJ/mt)
Softwood	340	80	22,83
Hardwood	340	80	22,50
Straw	345	60	20,69
Palm Shells	350	90	25,32

(LHV is the lower heating value, also known as net calorific value or net CV)

The inventors have also found that the method of the present invention allows for the operation of the process at a point which achieves coal-like properties with minimal loss of volatiles., i.e. minimal weight loss. Without wishing to be bound by theory, it is believed that the coal-like properties, such as brittleness and a breakdown of fibrous structure, arise from the cracking of hemi-celluloses in the feedstock. Cracking of the less reactive lignin is undesirable since it is this component that determines the compacting behaviour of the product. If the lignin is cracked then the treated material becomes less sticky and harder to compact.

The inventors have found that the toroidal bed reactor used in the present invention is uniquely capable of achieving this fine balance of cracking the hemi-celluloses rather than the lignin in the reaction times used. This fine balance allows for minimal volatiles losses of around 15-20% and the production of a product with around 22 GJ/mt in very little time. The inventors studies show that higher energy materials may be produced, such as 31 GJ/mt, although this is associated with a greater weight loss (60-70%).

25

In the following passages different aspects/embodiments of the invention are defined in more detail. Each aspect/embodiment so defined may be combined with any other aspect/embodiment or aspects/embodiments unless clearly indicated to the contrary. In particular, any feature indicated as being preferred or advantageous may be combined with any other feature or features indicated as being preferred or advantageous.

The invention will also be described with reference to the figures, provided by way of example, in which:

10

Figure 1 shows a toroidal bed reactor of the type disclosed in EP1791632; Figure 2 shows a flowchart of the process in accordance with the present invention; and Figure 3 shows ignition ability results of various materials.

15

An oxygen depleted atmosphere, as used in the present invention, has an oxygen content of less than 10% oxygen by volume, still more preferably less than 2%. Most preferably there is substantially no oxygen present (less than 1%, or less than 0.5%). This reduces the risk of the biomass feedstock spontaneously combusting. Preferably there is substantially no oxygen present. Preferably the gas or gases used in the toroidal bed reactor comprise super heated steam and/or an inert gas and/or a recycled process gas stream.

20

It is believed that the low residence times that are achievable by the torrefaction process of the present invention renders the undesirable presence of oxygen less critical. While it is desirable to minimize the contact of the feedstock with oxygen during treatment, it is believed that due to the relatively brief time that the feedstock is at high temperature, undesirable oxidation is avoided. Therefore, the process can be operated in the presence of some oxygen, whereas prior art methods require substantially no oxygen to be present.

25  
30

Any biomass or biomaterial is suitable for use in the torrefaction process. Biomass is biological material derived from living, or recently living organisms. Biomass is carbon based and is composed of a mixture of organic molecules containing hydrogen, usually including atoms of oxygen, often nitrogen and also small quantities of other atoms,

including alkali, alkaline earth and heavy metals. Examples of biomass include wood, plant matter and waste (including sewage sludge and agricultural residues). Wood includes forest residues such as dead trees, branches and tree stumps, yard clippings, wood chips and process residues. Plant matter includes biomass grown from, for  
5 example, miscanthus, switchgrass, hemp, corn, poplar, willow, sorghum or sugarcane, and includes straw and husks. Preferably the biomass treated has a solid form and a useful calorific value. If the calorific value is too high or too low then the biomass may be initially homogenized to provide a feedstock of substantially uniform calorific value.

10 Preferably the biomass feedstock comprises wood or a wood derivative. Wood may be used in any form, but preferably in the form of chips (1 to 5 cm thick) or chunks (5 to 10 cm thick). Wood derivatives include wood derived products such as MDF sheets or furniture, or processed wood composites. Preferably these are also in the form of chips  
15 or chunks. An initial pre-treatment step may be required, depending on the feedstock to obtain the desired particle size. In other embodiments other biomass may be treated such as palm shells and/or straw.

In one embodiment, the present process may be used as a method of recycling by transforming waste wood products into a useful high calorific value biofuel.

20

The torrefaction step (i) preferably heats the biomass feedstock to a temperature of from 280 to 400°C. More preferably the torrefaction step (i) heats the biomass feedstock to a temperature of from 320 to 350°C, and most preferably about 335°C. The heat may be supplied by using heated gas or gases, or by heating the furnace itself so that the gases  
25 within the furnace become heated, or by a combination of the two approaches.

Preferably this heat is provided by combustion of torrefaction gases produced in the process. These may be removed from the reactor and optionally treated, before being burnt to produce the heat energy required.

30 While conventional techniques using ovens and kilns heat the wood for from 10 to 12 minutes at 280-320°C, the process of the present invention may be performed in around 1 minute at a higher temperature of preferably 320 to 350°C. Alternatively, due to the excellent mixing of the particles, lower temperatures (down to 280°C) may still be used and a short residence time is still sufficient to fully torrefy the biomass.

Preferably the biomass feedstock has a residence time of less than 5 minutes in the toroidal bed reactor in step (i). This is to avoid scorching or over decomposition of the biomass material. It is preferred that the biomass feedstock has a residence time of less than 120 seconds, and more preferably less than 60 seconds, in the toroidal bed reactor in step (i), although at least 30 seconds residence time is preferred. Residence time, as used herein means the mean duration of time that an average piece of biomass feedstock spends in the toroidal bed reactor at the set reaction temperature.

10 Preferably the flow of fluid within the reaction chamber has a horizontal and a vertical velocity component. This may be provided by using a chamber having a plurality of outwardly radiating inclined fluid inlets at or adjacent a base thereof, and wherein fluid is directed through the fluid inlets at the base of the chamber to generate the circumferentially directed flow of fluid within the chamber. Preferably the fluid directed through said fluid inlets is given both horizontal and vertical velocity components.

In an embodiment of the process, the process further comprises a devolatilization step of heating the biomass feedstock to between 200 and 280°C before performing step (i). This step may be performed in a conventional oven, for example, with the biomass passing on a conveyor belt through a heated chamber. Such high temperature devolatilization techniques are well known in the art. Alternatively, the devolatilization may be performed in a further toroidal bed reactor. The heat for pre-volatilization may be obtained using heat exchange from the product or from energy obtained by combusting the torrefaction gases produced by the torrefaction process.

25 Preferably the biomass feedstock is subjected to at least one pre-treatment step selected from picking, milling, screening, mixing and blending. This homogenizes the biomass and ensures that even residence times can be achieved. Thus a constant level of torrefaction can be achieved and the calorific value of the product kept substantially constant.

Picking is the removal of outsized portions of the feedstock. Milling is the grinding reduction in the size of particles of the feedstock. Screening, blending and mixing are

steps used to ensure a homogeneous feedstock in terms of particle size, consistency and chemical make-up respectively.

The biomass feedstock may be dried at a temperature of from 100 to 200°C before use.

5 This low temperature step may be used to reduce the moisture content of the biomass before treatment. This serves to reduce the energy requirement for heating the treated product. This may be performed in a conventional oven or a still further toroidal bed reactor. As with the optional devolatilization step, the energy for the drying step may be advantageously obtained using heat exchange.

10

Advantageously, the energy for performing the drying and/or the devolatilizing step and/or the torrefaction step may be obtained from combustion of the volatile gas from the biomass feedstock. The volatile gases are driven off during any heating of the biomass and may be collected and conserved for this purpose. The combustible volatile gas  
15 typically comprises one or more of carbon monoxide, hydrogen, and low molecular weight hydrocarbons, the proportions varying between different sources. The combustion of the volatile gases may be used to supplement other energy or heat sources.

20

Preferably the biomass feedstock has a water content of 20% or less, more preferably 10% or less, before step (i). This minimizes the heating required and hence accelerates the speed of the torrefaction step (i).

25

Advantageously, the use of a toroidal bed reactor allows the process to be operated as a continuous process for the torrefaction of a biomass feedstock. This allows for fast  
product of a biofuel and for low energy costs since it does not need to be performed in  
batches with set-up and wind-down energy demands.

30

In step (i), the biomass feedstock may be fed into the toroidal bed reactor via an airlock system to prevent the loss of heat or the introduction of undesirable oxygen.

The process of the present invention is carried out in a toroidal bed reactor. A toroidal bed (TORBED (RTM)) reactor and process is described in EP 0068853, US 4479920, and EP 1791632, the disclosures of which are incorporated here by reference. In the process, a material to be treated is embedded and centrifugally retained within a

compact, but turbulent, toroidally circulating bed of particles which circulate about an axis of the processing chamber. Specifically, the material forms particles within the bed which are circulated above a plurality of fluid inlets arranged around the base of the processing chamber. The fluid inlets are preferably arranged in overlapping relationship and the particles are caused to circulate around the bed by the action of a processing fluid, for example a gas injected into the processing chamber from beneath and through the fluid inlets. The fluid inlets may, for example, be a plurality of outwardly radiating, inclined vanes arranged around the base of the processing chamber.

10 By way of example, Figure 1 shows a schematic diagram of a toroidal bed reactor 1. The gaseous fluid (A) mixed with the feedstock enters through angled vents 9 in the base of the reaction chamber 3. The path of the turbulent flow in the reaction chamber 3 is shown by the spiralling arrows marked (E). The dotted arrows show the circulation pathway (in 2 dimensions only) taken by the feedstock that is to be processed.

15 The toroidal bed reactor provides a rapidly mixing bed which can be used to circulate particulates toroidally through a zone in a process chamber where an interaction occurs with a gas stream.

20 Preferably a toroidal bed reactor for use in the present invention has a reaction chamber with a substantially circumferentially directed flow of fluid generated therein to cause the biomass feedstock to circulate rapidly about an axis of the reaction chamber in a toroidal band, and to heat the biomass feedstock, wherein the fluid comprises gas or gases introduced into the reaction chamber. Preferably the flow of fluid within the reaction chamber has a horizontal and a vertical velocity component. Preferably the chamber comprises a plurality of outwardly radiating inclined fluid inlets at or adjacent a base thereof, and wherein fluid is directed through the fluid inlets at the base of the chamber to generate the circumferentially directed flow of fluid within the chamber. Preferably the fluid directed through said fluid inlets is given both horizontal and vertical velocity components.

The biomass feedstock may be introduced into the reactor(s) by injecting it through an inlet under the influence of a compressed gas such as compressed air and/or an inert gas such as nitrogen, CFC and other noble/mono-atomic gases. In a preferred

embodiment of the present invention, the inlet is located above the fluid inlets at the base of the chamber and the biomass feedstock is introduced into the chamber by a gravity feed mechanism, for example using an air lock device such as a rotary valve. The gravity feed mechanism may be provided in a vertical wall of the chamber.

5

It will be appreciated that the flow of fluid may be generated either before or after the biomass material is introduced into the chamber. Alternatively, the flow of fluid may be generated at the same time as the biomass material is introduced into the chamber.

10 The flow of the fluid through the chamber may be generated in a manner as described in EP-B-0 382 769 and EP-B-0 068 853, i.e. by supplying a flow of fluid into and through the processing chamber and directing the flow by means of the plurality of outwardly radiating and preferably overlapping fluid inlets arranged in the form of a disc and located at or adjacent to the base of the processing chamber. The fluid inlets are  
15 inclined relative to the base of the chamber so as to impart rotational motion to the heating fluid entering the chamber, hence causing the heating fluid to circulate about a substantially vertical axis of the chamber as it rises. The fluid inlets may comprise, for example, a plurality of outwardly radiating vanes at or adjacent the base of the chamber. The vanes are typically inclined relative the base and preferably disposed in overlapping  
20 arrangement.

The solid char product produced by the process of the present invention is a higher calorific value per unit weight than the biomass feedstock. It also has a more constant calorific value. The processing has been found to provide a unique product compared to  
25 conventional methods in that, the product has improved ignitability (lower temperature to ignite) and increased hydrophobicity (and hence better potential for being stored). Without wishing to be bound by theory, it is believed that this arises by virtue of an increased surface area of the product that arises from the novel process. Thus, it is an excellent biofuel.

30

The biofuel may be the direct product from the torrefaction of the biomass. Alternatively, a further finishing step may be used to produce a granular, briquette sized, or lump-sized (preferably 5-10cm) biofuel. This may be achieved by introducing (for example, mixing or coating) a binder onto the torrefied biomass. This may occur either in the reactor or in a

finishing step, and can successfully agglomerate the torrefied biomass into a desirable size product. The term "agglomerate" as used herein refers to any process, such as pelletisation, that provides a consolidated fuel product. Suitable binders are well known in the art. In view of the outstanding homogeneity and increased calorific value of the produced biofuel, the biofuel is considered novel over such fuels made by conventional techniques.

In one embodiment of the process of the present invention, the process further comprises a step of mixing the torrefied biomass with coal, preferably in an amount of from 90% to 75% coal by weight of the mixture of biomass and coal. That is, to produce a biofuel comprising from 10 to 25% by weight of the biofuel obtainable according to the process of the invention and the balance coal. In a preferred embodiment the coal is present in an amount of from 85 to 80% by weight, i.e. 15 to 20 % by weight of torrefied biomass. This is especially advantageous as this mixture allows for a decrease in the ignition temperature of the coal. For some coals their ignition temperature is unfavorably high and so may struggle to burn in a conventional reactor. The admixture of the most combustible torrefied material can be used to decrease the temperature at which the coal will stably burn. Preferably the mixture is with a coal having an ignitability of less than 6 kJ/kg coalX, and more preferably less than 5.5 kJ/kg coal°C, such as Kleinkopje coal. These are typically "hard" coals.

The homogeneous nature of the biofuel produced by the present method facilitates mixing with the coal to provide a final fuel having substantially homogeneous calorific properties. The biofuel may be ground to allow easy mixing with the coal.

In one embodiment, the process comprises the torrefaction of a biomass feedstock for the production of a biofuel, the process comprising:

- (i) torrefaction of a biomass feedstock comprising wood or a wood derivative in a toroidal bed reactor,
  - wherein the toroidal bed reactor comprises a reaction chamber with a substantially circumferentially directed flow of fluid generated therein to cause the biomass feedstock to circulate rapidly about an axis of the reaction chamber in a toroidal band, and to heat the biomass feedstock, wherein the fluid comprises gas or gases

introduced into the reaction chamber and wherein the chamber is maintained under an oxygen-depleted atmosphere,

wherein the biomass feedstock is dried at a temperature of from 100 to 200°C before use. and wherein the process further comprises a devolatilization step of heating the biomass feedstock to between 200 and 280°C before performing step (i) to provide the biomass feedstock with a water content of 20% or less before step (i). This combination of processes has been found to be particularly efficient in the processing of the wood feedstock.

The process of the present invention will now be briefly summarized with reference to Figure 2. Figure 2 is a flow chart summarizing the steps of the present invention. It should be noted that several of the steps such as pre-treatment A', drying B', heat recycling with a combustor D', agglomerating and/or burning as a fuel, are optional steps.

Wood chippings 5 which serve as a biomass feedstock are subjected to an initial pretreatment A' in which they are picked and sized to ensure that a substantially homogeneously proportioned feedstock is used. The feedstock is then dried in an oven at 150°C for 30 minutes in a drying step B'.

The dried wood chippings 5 then pass into a toroidal bed reactor in a treatment step C . Here the chippings 5 are subjected to a temperature of 335°C for on average 60 seconds. This produces a gas comprising volatiles 10 and a torrefied material 15.

The volatiles 10 are passed to a combustor D', where in combination with additional natural gas 20 they are combusted. This provides hot gases which are used to provide heat to both the drying step B' and the treatment step C

The torrefied material 15 is gathered from the toroidal bed reactor in a hopper E'. The material 15 may then be treated in one of various ways to produce a biofuel 30 which can be combusted in, for example, a power station H' to produce energy. Firstly, the torrefied material 15 can be used as it is as the biofuel 30. Secondly, the material 15 can be subjected to a compaction process step G', optionally with a binder, to produce even-sized pellets (i.e. 5cm briquettes). Thirdly, the material 15 can be mixed with another fuel

such as a poorly ignitable coal before pelletisation in a compaction process step G' to provide a biofuel 30.

The product of the present invention will now be shown in the following non-limiting example in which the properties of beechwood CPM<sup>tm</sup> pellets, coal pellets and blends of these two materials were investigated. In particular, the following fuels/fuel blends were tested:

- Kleinkopje coal (South Africa)
- Beechwood CPM<sup>tm</sup> pellets
- 10 - Blend Kleinkopje and beechwood CPM<sup>tm</sup> pellets 90%/10%
- Blend Kleinkopje and beechwood CPM<sup>tm</sup> pellets 80%/20%

The grinding behaviour of coals in power station milling plants with a classification system, as determined by energy demand and capacity of the milling plants, does not only depend on the hardness (solidity) of the coals. Rather it also depends on the particle size (fine grain fraction) of the shipment, the classifying behaviour in the milling plant, the compressive force in the mill and, in particular, on the expected particle size of the pulverised coal.

20 The results of the investigation are set out below in Tables 2a-d. These demonstrate that the wood can be ground faster (lower cycle factor), but takes more energy to be ground. Surprisingly the blends grind faster than either the coal or the wood alone and the energy cost for the grinding is comparable to that of the coal alone.

25 Table 2a

<b>Kleinkopje</b>	
<b>Results (Average results of the 2 last cycles)</b>	
<b>generated particulate matter [%]</b>	<b>19.5</b>
<b>Cycle factor</b>	<b>4.17</b>
<b>Specific grinding energy [J/g sample]</b>	<b>6.94</b>
<b>Specific Comminution work:</b>	
<b>[J/g sample]</b>	<b>28.98</b>
<b>[kWh/t sample]</b>	<b>8.05</b>
<b>force application angle beta</b>	<b>85.80</b>

Table 2b

<b>Beechwood CPM pellets</b>	
<b>Results (Average results of the 2 last cycles)</b>	
generated particulate matter [%]	22.08
Cycle factor	3.92
Specific grinding energy [J/g sample]	12.96
<b>Specific Comminution work:</b>	
[J/g sample]	50.79
[kWh/t sample]	14.11
force application angle beta	87.73

Table 2c

<b>Blend (Kleinkopje/Pellets (90%/10%))</b>	
<b>Results (Average results of the 2 last cycles)</b>	
generated particulate matter [%]	22.79
Cycle factor	3.69
Specific grinding energy [J/g sample]	8.50
<b>Specific Comminution work:</b>	
[J/g sample]	31.41
[kWh/t sample]	8.72
force application angle beta	86.53

5 Table 2d

<b>Blend (Kleinkopje/Pellets (80%/20%))</b>	
<b>Results (Average results of the 2 last cycles)</b>	
generated particulate matter [%]	25.57
Cycle factor	3.30
Specific grinding energy [J/g sample]	9.27
<b>Specific Comminution work:</b>	
[J/g sample]	30.52
[kWh/t sample]	8.48
force application angle beta	86.77

The ignition temperature parameter describes the ability of a fuel to form a stable coal flame. The manner in which a flame subsequently develops during the combustion process depends on the combustion conditions in the boiler and the degree of reactivity the fuel has with regard to its basic organic matrix.

When assessing coals and/or coal blends, the ignitability represents an essential parameter to characterise the formation and development of a coal flame. This is based on the assumption that a stable coal flame forms when volatile matter is released from the coal prior to the ignition point. The ignitability parameter, the quotient of the ignition potential and the ignition temperature, represents a comparative parameter for the

5 ignition behaviour of different coals and coal blends.

$$ZWZ = \frac{N_{Z500}}{t_{Z150}} \left[ \frac{\text{kJ}}{\text{kgKohle} \cdot ^\circ\text{C}} \right]$$

The ignition potential ( $N_{Z500}$  in kJ/kg coal) is the chemical energy based on the fuel mass unit which is, up to a temperature of 500 °C, contained in the volatile decomposition products (based on a water-free fuel). It therefore corresponds to the heat content developing in the first phase of the combustion process, i.e. immediately after ignition. Therefore the ignition potential is a measurand which allows an assessment of the flame stability after ignition.

15

The ignition temperature ( $t_{Z150}$  in °C) is the gas temperature at which a pulverised coal sample ( $m=0.2$  g;  $d < 63$  µm) is injected into a preheated muffle furnace under defined conditions, where it is ignited with a delay of 150 ms in air. The delay time of 150 ms corresponds to the maximum ignition distance of 3 m from the burner tip and a

20 pulverised coal-air blend with a flow velocity of 20 m/s.

The results are shown in Figure 3 which shows a plot of the ignitability of various coal types and fuel sources. From left to right, these are: Polen, Prosper-Haniel, Appalachenkohle, Norweigan, Russland, US Steam 1,3%S, US Steam 2,0%S, Douglas,

25 Kleinkopje CPM-pellets 90/10 Blend, 80/20 Blend. The x axis shows the ignitability parameter. The y-axis shows ZWZ in kJ/Kg Coal °C. Section A shows fuels that burn satisfactorily with no problems and a stable flame. Section B shows fuels with unsatisfactory ignitability or no ignition at all. As can be seen, the blending of the coal with CPM-pellets allows it to be increased in ignitability and an 80/20 blend provides a useful

30 fuel.

When comparing the expected grinding behaviour of Kleinkopje coal to the one of beechwood CMP pellets, the clearly higher result of the pellets in connection with the specific comminution work is immediately noticeable. When grinding Kleinkopje coal, merely 8.05 kWh are required for each ton of generated pulverised coal. For the pellets, however, almost 1.8 times the energy is necessary. In this case, the result is 14.11 kWh/t. However, with 4.17, the cycle factor for coal is slightly higher than the one for the pellets with 3.92. It should be noted that both results appear relatively high in comparison to earlier tests on fuels.

10 The test results show that approximately 1.9 times the energy (12.96 J/g samples required for the grinding of beechwood CPM pellets compared to Kleinkopje coal (6.94 J/g sample).

15 Preparing blends from these two fuels affects the grinding process in a most favourable manner. Two blends were prepared for the test, which were composed as follows:

Blend 1 Kleinkopje and beechwood CPM pellets 90%/10%

Blend 2 Kleinkopje and beechwood CPM pellets 80%/20%

20 Although the comminution work increases slightly in comparison to the pure coal (~8% (8.72kWh/t pulverised coal) in admixture with 10% pellets), this additional energy demand is not significant. When adding 20% biofuel to the coal, the comminution work increases by ~5% (8.48 kWh/t pulverised coal) only and is therefore smaller than with the lower dosage.

25 The result for the cycle factor is very satisfactory. Compared to the initial result of the coal, this value drops by approximately 13% for Blend 1 and by about 26% for Blend 2. This means, the result of 3.30 for Blend 2 has reached a range which is by all means typical for imported and domestic coals.

30 Another positive aspect is the fact that the generated particulate matter of 19.50% for Kleinkopje coal increases to 22.79% for Blend 1 and to as much as 25.57% for Blend 2.

However, an overall higher energy demand was noted for the grinding process. This is because the value of the specific grinding energy rises from 6.94 J/g sample to 8.50 J/g sample (Blend 1) and 9.27 J/g sample (Blend 2).

5 Coals with a high ignition potential reach higher temperatures immediately after ignition when burning in a pulverised coal flame. This causes such a pulverised coal flame to become "more stable". Due to the fact that:

- the better the ignition behaviour of a coal is, the greater its ignition potential; and
- 10 - the worse the ignition behaviour of a coal is, the higher the ignition temperature.

When comparing Kleinkopje coal to beechwood CMP pellets, the significant difference with regard to the ignitability parameter is immediately noticeable. Kleinkopje coal has a ZWZ of only 5.79 kJ/kg coal°C thus remaining below the limit of 6 kJ/kg coal°C.

15 Experience has shown that in order to ensure stable conditions in the furnace, the value should not drop below this limit. Otherwise, this could result in an unsatisfactory ignitability in the power plant. The pellets, however, have a relatively high ZWZ of 11.36 kJ/kg coal°C. For this reason, no problems are expected with regard to the formation of a stable flame when employing this fuel.

20

The favourable ignitability characteristics of the pellets are based on a very low ignition temperature and a very high ignition potential. With 556°C, the ignition temperature of the pellets is more likely to be attributed to the range of lignite coals. Here, this hard coal (Kleinkopje) has a clearly higher ignition temperature of 808°C.

25

Although the biofuel's ignition potential of 6.32MJ/kg is clearly higher than the coal's with 4.68MJ/kg, it is not considered a particularly high value. The pellets are expected to ignite well, but the reaction will most likely not take place explosively in a manner to where it could cause problems in the burner.

30

If consideration is given to blending pellets to the coal for the purpose of improving the comparably inadequate ignitability, an addition of 10% would not necessarily be sufficient (5.55 kJ/kg coal°C). This would depend on the coal. However, adding 20% of pellets, which equals 6.59 kJ/kg coal°C in this case, would satisfy the requirements of aZWZ

larger than 6 kJ/kg coal\*°C. It can therefore be assumed that, in this case, no problems would occur in the furnace.

Blend 1 (90% coal/ 10% pellets) has an ignition temperature of 785°C and an ignition potential of 4.36 MJ/kg. Blend 2 (80% coal/ 20% pellets) has an ignition temperature of 698°C and an ignition potential of 4.60 MJ/kg.4.

The conducted tests confirm that the beechwood CPM pellets, up to a content of 20%, influence the quality characteristics to a minor extent only. However, they positively affect the combustion-related parameters. This means:-

Ignition temperature:

The lignite-like CMP pellets cause the ignition temperature of the tested blends to drop to a temperature range which is relatively low for hard coals. This means that a relatively quick ignition can be expected. Given that the combustion technique is appropriate, this circumstance affects the burnout behaviour in a positive manner

Ignitability:

Selecting Kleinkopje coal as a hard coal meant selecting a coal quality which is not necessarily suitable for an unrestricted use in all types of firing systems. This coal must generally be ground much finer in order for the coal to meet the demands of the power plant with regard to its ignition and burnout behaviour. When assign the pellets, the ignitability and the formation of a stable flame are enhanced within a range typical for hard coals (with a dosage rate of 20%).

Grinding behaviour:

The required comminution work in AVT-like milling plants is considerable. We do not recommend the sole employment of pellets because the energy demand is approximately 70% higher than for Kleinkopje coal which, in comparison, is much harder. However, blends frequently have characteristics which reflect the major component of a blend, and this applies to coal blends as well. The exact opposite applies to the cycle factor. It is reduced by approximately 20% when adding the pellets. Therefore the mill flow rate will most likely remain ensured.

Although preferred embodiments of the invention have been described herein in detail, it will be understood by those skilled in the art that variations may be made thereto without departing from the scope of the invention or of the appended claims.

**Claims:**

1. A process for the torrefaction of a biomass feedstock for the production of a biofuel, the process comprising:
  - 5 (i) torrefaction of a biomass feedstock in a toroidal bed reactor, wherein the toroidal bed reactor comprises a reaction chamber with a substantially circumferentially directed flow of fluid generated therein to cause the biomass feedstock to circulate rapidly about an axis of the reaction chamber in a toroidal band, and to heat the biomass feedstock, wherein the fluid comprises gas or gases
- 10 introduced into the reaction chamber and wherein the chamber is maintained under an oxygen-depleted atmosphere.
2. A process according to claim 1, wherein the gas or gases comprises super heated steam and/or an inert gas.
- 15 3. A process according to claim 1 or claim 2, wherein the biomass feedstock comprises wood or a wood derivative.
4. A process according any of the preceding claims, wherein the torrefaction step (i) heats the biomass feedstock to a temperature of from 280 to 400°C.
- 20 5. A process according to claim 4, wherein the torrefaction step (i) heats the biomass feedstock to a temperature of from 320 to 350°C
- 25 6. A process according to any of the preceding claims, wherein the biomass feedstock has a residence time of less than 5 minutes in the toroidal bed reactor in step (i).
7. A process according to claim 6, wherein the biomass feedstock has a residence time of less than 60 seconds in the toroidal bed reactor in step (i).
- 30 8. A process according to any of the preceding claims, wherein the flow of fluid within the reaction chamber has a horizontal and a vertical velocity component.

9. A process according to any of the preceding claims, wherein the chamber comprises a plurality of outwardly radiating inclined fluid inlets at or adjacent a base thereof, and wherein fluid is directed through the fluid inlets at the base of the chamber to generate the circumferentially directed flow of fluid within the chamber.
- 5
10. A process according to any of the preceding claims, wherein fluid directed through said fluid inlets is given both horizontal and vertical velocity components.
11. A process according to any of the preceding claims, wherein the process further  
10 comprises a devolatilization step of heating the biomass feedstock to between 200 and 280°C before performing step (i).
12. A process as claimed in any of the preceding claims, wherein the biomass feedstock is subjected to at least one pre-treatment step selected from picking, milling,  
15 screening, mixing and blending.
13. A process according to any of the preceding claims, wherein the biomass feedstock is dried at a temperature of from 100 to 200°C before use.
- 20 14. A process according to any of the preceding claims, wherein the biomass feedstock has a water content of 20% or less before step (i).
15. A process according to claim 14, wherein the water content is 10% or less.
- 25 16. A process according to any of the preceding claims, wherein step (i), an optional drying step and/or an optional devolatilizing step, produce a volatile gas from the biomass feedstock which is combusted to at least partly provide the heat required by one or more steps of the process.
- 30 17. A process according to any of the preceding claims, wherein the torrefaction of the biomass feedstock is performed as a continuous process.
18. A process according to any of the preceding claims, wherein a final agglomerating step is performed to provide a granular or briquette-sized biofuel.

19. A process according to any of the preceding claims, wherein the process further comprises a step of mixing the torrefied biomass with coal, preferably in an amount of from 90% to 75% by weight coal.

5

20. A biofuel obtainable according to the process of any of the proceeding claims.

21. A biofuel comprising from 10 to 25% by weight of the biofuel obtainable according to the process of any of claims 1 to 18, and the balance coal.

Figure 1

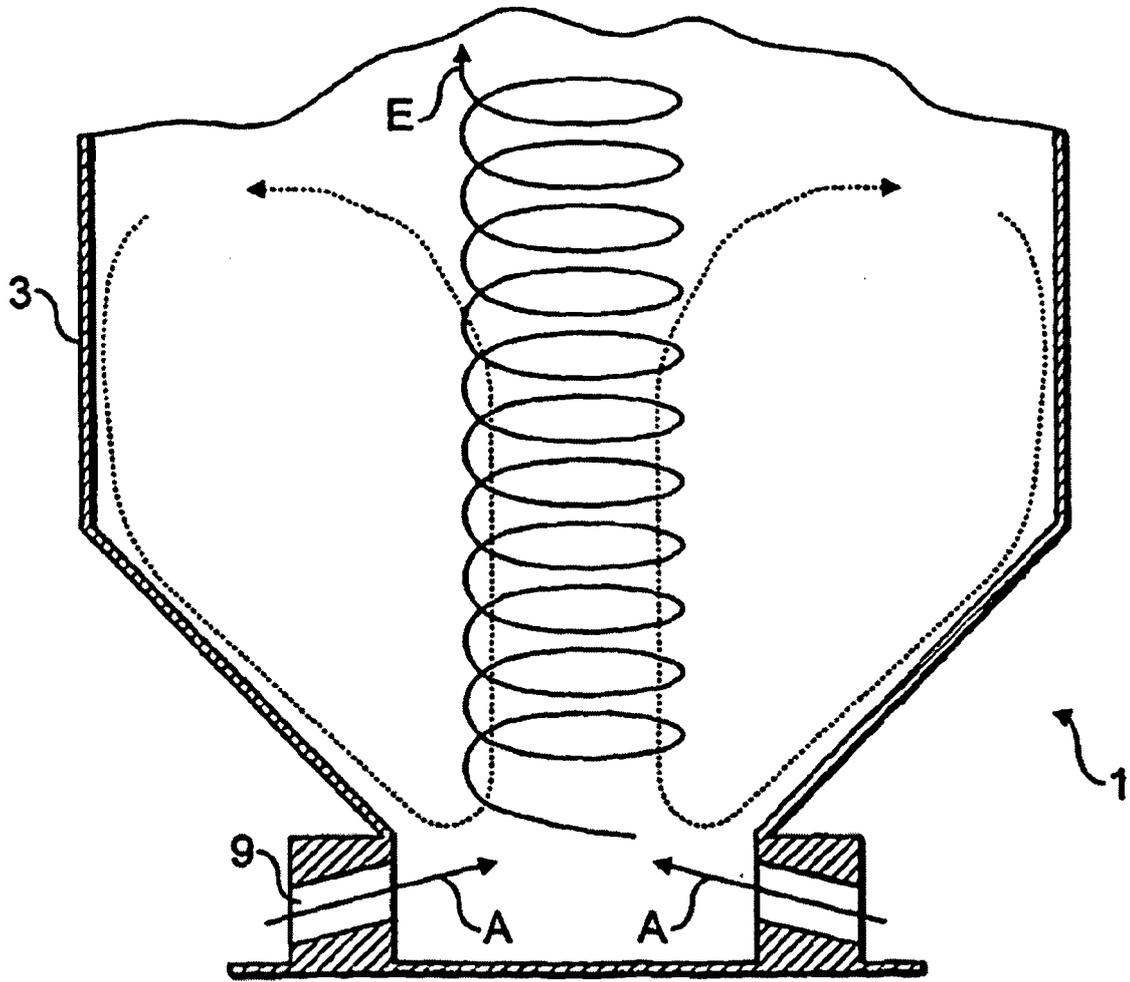


Figure 2

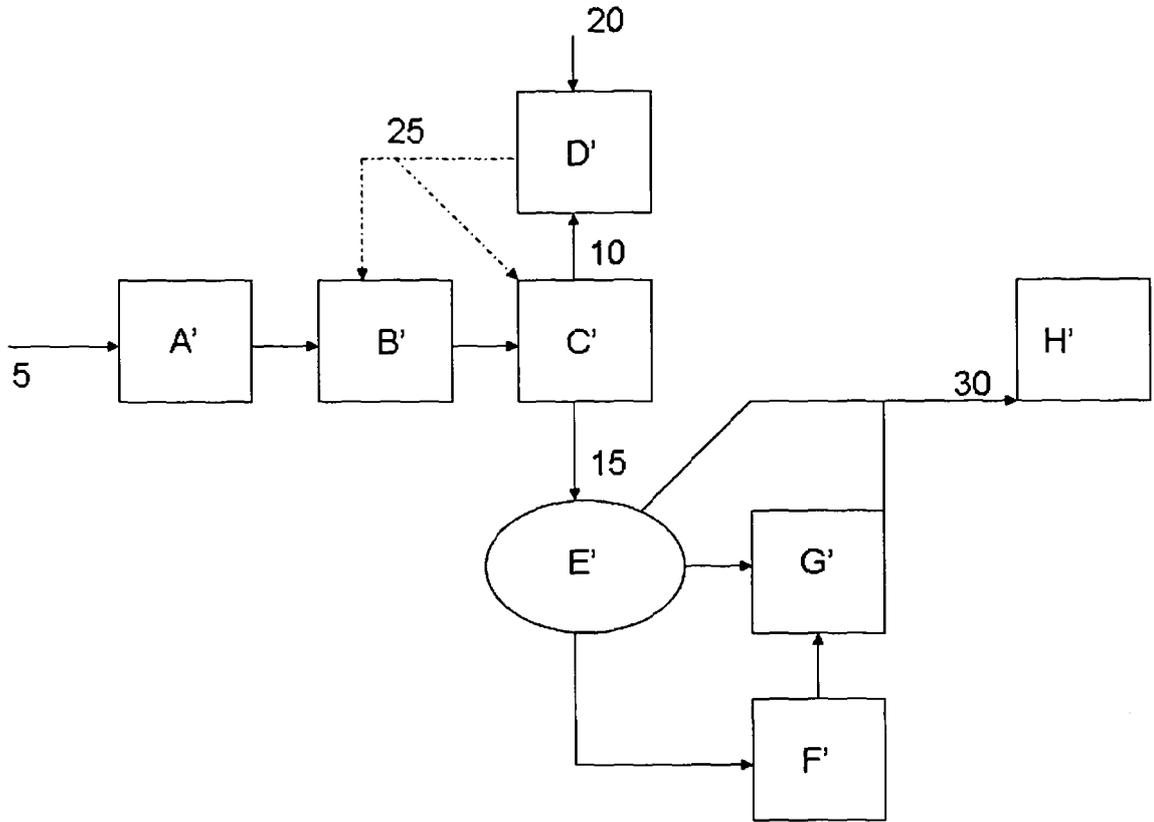
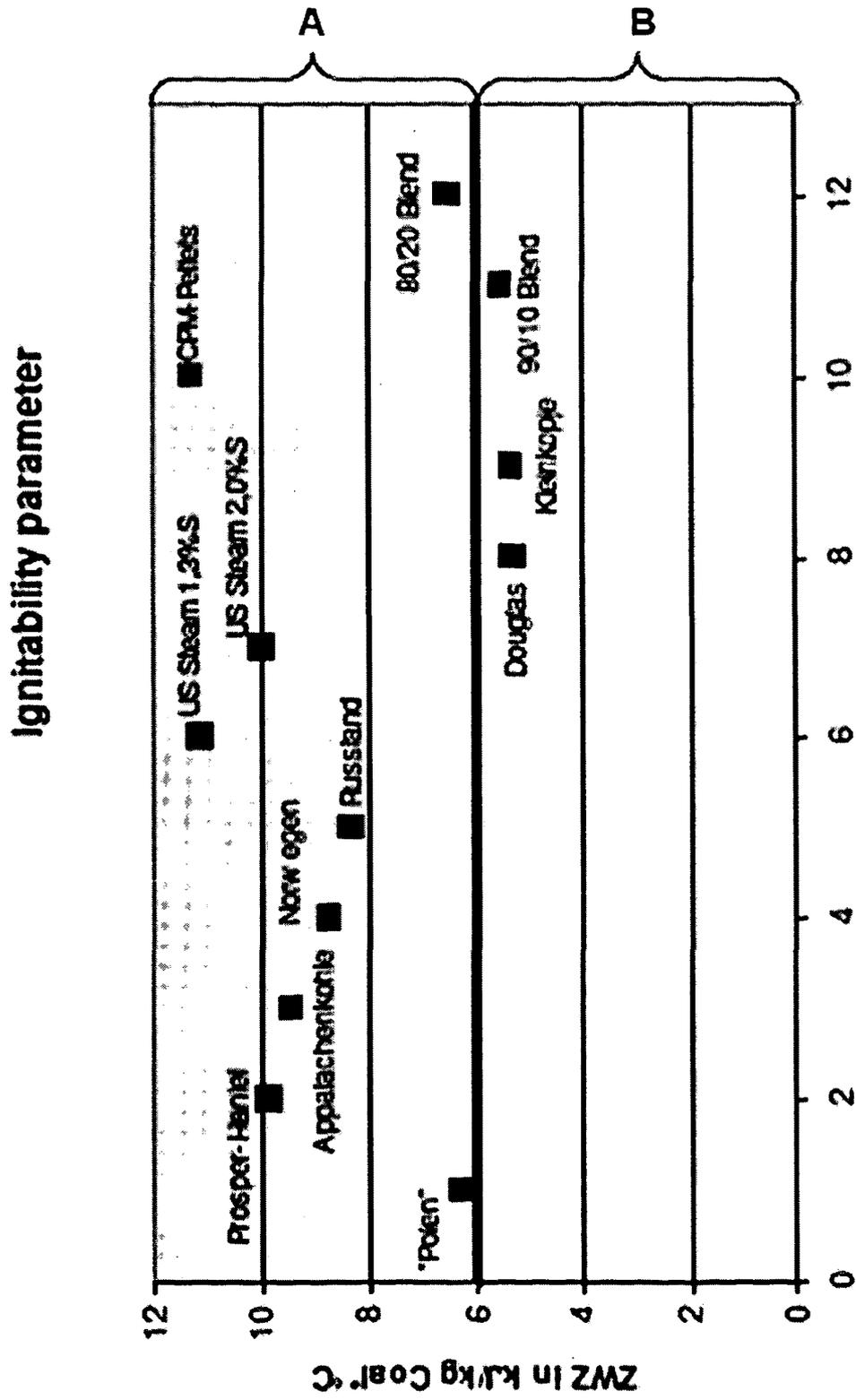


Figure 3



# INTERNATIONAL SEARCH REPORT

International application No <b>PCT/GB2011/000660</b>
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A. CLASSIFICATION OF SUBJECT MATTER  
**INV. C10L5/44 B01J8/00 C10B49/02 C10B53/02 F26B1/00**  
**F26B25/00**

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
**CIOL B01J CIOB F26B**

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**EPO-Internal**

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
<b>A</b>	<p><b>LAKSHMANAN V I ET AL: "AN INNOVATIVE GAS-SOLID TORBED REACTOR FOR THE RECYCLING INDUSTRIES",</b>  <b>J O M, SPRINGER NEW YORK LLC, UNITED STATES,</b>                      vol . 50, no. 7, 1 July 1998 (1998-07-01) ,                      pages 29-31 , XP000791570,                      ISSN: 1047-4838                      page 29; figure 1</p> <p style="text-align: center;">----- -/- .</p>	<b>1-21</b>

Further documents are listed in the continuation of Box C.       See patent family annex.

\* Special categories of cited documents :

<p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&amp;" document member of the same patent family</p>
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Date of the actual completion of the international search <b>11 August 2011</b>	Date of mailing of the international search report <b>27/09/2011</b>
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer  <b>Bertrand, Samuel</b>
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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2011/000660

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 244853 1	A	NON E	
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