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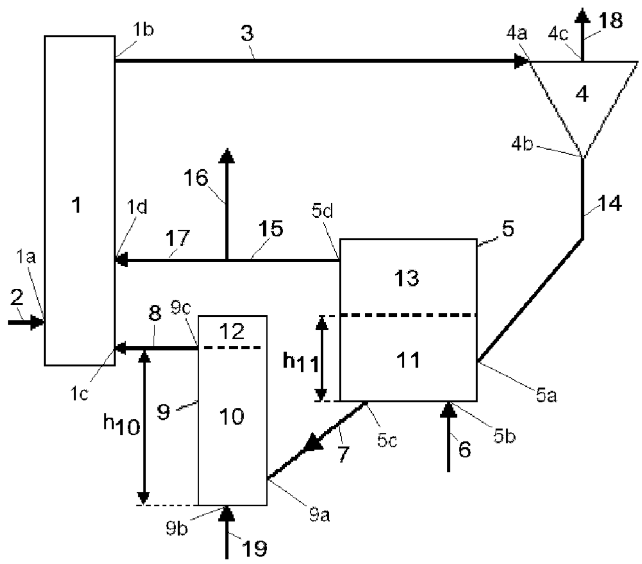

Fig. 1

(57) Abstract: The invention relates to a circulating fluidized bed (CFB) reactor for thermal processing of added carbonaceous material, the carbonaceous material normally comprises organic material or organic material mixed with inorganic material such as in straw or other vegetable waste, manure, household rubbish, dried wastewater, dried animal remains or other dried carbonaceous waste products. The invention also relates to a process for manufacturing a combustible product gas having a heating value around 4-8 MJ/Nm3 from such a carbonaceous material by subjecting the carbonaceous material to pyrolysis in one process step and oxidation in two subsequent process steps. A circulating fluidized bed (CFB) reactor according to the invention comprises a primary char gasification chamber (5) and an intermediate char gasification chamber (9) typically provided with a fluidized bed wherein the height (h10) of the second fluidized bed (10) in the intermediate char gasification chamber is larger than the height (hn) of the first fluidized bed (11) in the primary char gasification chamber (5).

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Apparatus and methods for gasification

Field

The invention relates to circulating fluidized bed (CFB) reactors for thermal processing of added carbonaceous material, and to processes for manufacturing combustible product gas having a higher heating value between 4-8 MJ/Nm^3 from such a carbonaceous material by subjecting the carbonaceous material to pyrolysis in one process step and oxidation in another process step.

Background

The document WO 99/32583 discloses a method and apparatus for gasification of solid carbonaceous material comprising a circulating fluidized bed (CFB) gasifier constituted as described in Figure 1 of the document by a pyrolysis reaction chamber (1), a particle separator (2) for separation of char-containing particles from the outlet gas (32) of the pyrolysis reaction chamber, a char reaction chamber (3), having at least one inlet for particles from the particle separator, and means for further recirculating particles from the char reaction chamber to the pyrolysis-reaction chamber. The dual chamber CFB gasifier's operation may be controlled in different ways. The disclosed apparatus and process functions well at comparatively low temperatures, beneath 750o C. Due to this success at unusually low and well controlled temperatures, this system is particularly well suited for organic biomass, waste streams and energy crops which contain a relatively high concentration (> 0.2%) of elements such as Potassium and Phosphorus, which tend to exist in or form low melting ash components.

Decomposition of added carbonaceous material by the previously disclosed apparatus can be increased by adding extra fluidized bed reaction chambers between the primary char reaction chamber, where char particles are gasified, and the pyrolysis reaction chamber, where new carbonaceous fuel material is added. This effectively increases the reactor volume available for char treatment and thereby increases the degree of decomposition of char remaining after initial treatment in the pyrolysis reaction chamber. However, serial positioning of one or more fluidized bed char reaction chambers between the recirculating separator and the pyrolysis reaction chamber (1) can cause temperature control problems. The temperature tends to increase in each subsequent fluidized bed char reaction chamber because the char decomposition reactions are primarily exothermic, in contrast with the primarily endothermic pyrolysis reactions which prevail in the pyrolysis chamber. In normal operations, it is generally advantageous to maintain the primary char reaction chamber at a temperature that is as high as possible, but still beneath the threshold for ash agglomeration. Endothermic pyrolysis reactions typically drive the temperature in the pyrolysis reaction chamber down to levels on the order of 80 to 200 o C lower than the temperature in the primary char reaction chamber. A subsequent additional fluidized chamber placed between the primary char reaction chamber (3) and the pyrolysis reaction chamber (1) will, even if constituting as little as 10 % of the total char converting bed area,typically increase the overall maximum process temperature by an additional 5-20°C higher than the temperature in the primary char reaction chamber. This is disadvantageous because it either increases the risk of agglomeration of bed material in the extra fluidized char reaction chamber or necessitates a lowering of operation temperature in the primary char reaction chamber. This increased agglomeration risk is especially disadvantageous where the carbonaceous fuel material has a high content of alkaline, potassium, phosphorous and/or chlorine. In that case, even a small temperature increase can promote ash agglomeration, which can result in agglomeration of bed material leading to reactor shutdown.

These problems can be avoided by configuring the reactor so as to maximize gas and particle retention time in an "intermediate" char reaction chamber, and optionally, by using a higher steam to air ratio in the gasification agent added to the intermediate chamber. This provides a greater extent of endothermic, steam-based char decomposition reactions and, accordingly, a reduced tendency for increased temperature in the intermediate chamber.

Brief description of the drawings

Figure 1 shows one embodiment of a CFB reactor according to the invention indicating the relative position of units and conduits through which gas and particles flow.

Definitions

Mean temperature in a chamber refers to the temperature at a level corresponding to half the height of the chamber.

Detailed description of embodiments

In some embodiments, the invention provides a circulating fluidized bed (CFB) reactor for thermal processing of added carbonaceous material, comprising:

- a first pyrolysis reaction chamber (1) wherein added carbonaceous material is pyrolysed due to contact with hot recirculating particles, which first reaction chamber (1) has an inlet (1a) for carbonaceous material, an inlet (1c) for fluidizing gas, and an outlet (1b) for product gas in the upper part of the first reaction chamber (1) which product gas carries carbon containing char particles and recirculating inert particles,

- one or more separators (4) having an inlet (4a) through which the product gas carrying particles from the first reaction chamber (1) is received, and an outlet (4b) through which the particles leave each separator and enter into a primary char gasification chamber (5) via one or more conduits (14),

- said primary char gasification chamber (5) comprising an inlet (5a) for pyrolysed and recirculating particles, an inlet (5b) for fluidizing gas (6) in the lower part of the primary char gasification chamber (5), an outlet (5d) in the upper part of the primary char gasification chamber (5) for produced gas and an outlet (5c) for particles in the lower part of the primary char gasification chamber (5) opening into a particle return conduit (7) which particle return conduit (7) opens into an intermediate char gasification chamber (9), and

- said intermediate char gasification chamber (9), comprising an inlet (9a) for particles from the primary char gasification chamber (5) and an inlet (9b) for a fluidizing gas e.g. containing O_2/H_2O in the lower part of the reactor (9), and further comprising an outlet (9c) for produced gas carrying particles from the upper part of the chamber (9) which outlet (9c) opens into a conduit (8) having at least one outlet to the lower part of the first reaction chamber (1) and which provides fluidizing gas to the first reaction chamber (1).

In some embodiments, during operation a first fluidized bed (11) of particles is provided in the primary char gasification chamber (5), the volume of said first fluidized bed (11) is defined as the volume present above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the surface of the same fluidized bed, above the volume of the first fluidized bed (11) is a lower density freeboard volume (13) containing gas and entrained fine particles. In some embodiments, during operation particles are transported through the intermediate char gasification chamber (9) forming a second fluidized bed (10) of particles where the volume of said second fluidized bed (10) is defined as the volume above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the center of the outlet (9c) for produced gas and particles in the upper part of the intermediate char gasification chamber wherein the height (h_{10}) of the second fluidized bed (10) in the intermediate char gasification chamber (9) is larger than the height (h_{11}) of the first fluidized bed (11) in the primary char gasification chamber (5).

Alternatively, in some embodiments, during operation particles are transported through the intermediate char gasification chamber (9) forming a second fluidized bed (10) of particles where the volume of said second fluidized bed (10) is defined as the volume above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the center of the outlet (9c) for produced gas and particles in the upper part of the intermediate char gasification chamber wherein the pressure difference between the bottom and top of the primary char gasification chamber (5) is smaller than between the bottom and top of the intermediate char gasification chamber (9).

In some embodiments, a small amount of fluidizing gas (usually air), typically less than 15% of the flow of product gas, is added through nozzles distributed in the bottom of the pyrolysis chamber, in order to keep particles freely flowing and well mixed. In some embodiments, the reactor is configured such that nozzles through which fluidizing gas may be introduced are located within the bottom 15% of the pyrolysis chamber. As used herein a nozzle is located within the bottom 15% where the distance from the bottom surface of the pyrolysis chamber is 15% or less of the total distance between the bottom and top surface of the pyrolysis chamber.

In some embodiments, the reactor is configured such that the top of the intermediate char gasification chamber is placed at a level that is intermediate between the levels of the top and bottom of the primary char gasification chamber. In this context, the level is "intermediate" where it is at any level lower than the top and higher than the bottom of the primary char gasification chamber.

In some embodiments, the reactor is configured such that the top of the intermediate char gasification chamber (9) is placed at a level that is higher than that level of the primary char gasification chamber (5) at which the majority of fluidizing gas is introduced.

In some embodiments, the reactor is configured such that greater than 50% of the internal volume of the intermediate char gasification chamber is placed at a level beneath the level of the primary char gasification chamber at which the main part of fluidization gas is introduced.

According to an embodiment of the CFB reactor, the inlet (1c) for fluidizing gas and particles from the intermediate char gasification chamber (9) is positioned below i.e. upstream the inlet (1d) for gas from the fluidized bed char gasification chamber (5).

According to an embodiment of the CFB reactor, outlets for ashes can be provided from one or several of said reactors (1,5,9) as well as from one or several of the separators (4).

According to an embodiment of the CFB reactor, the cross-sectional area of the intermediate char gasification reactor is at least 50% and preferably at least 75%smaller than the cross-sectional area of the primary char gasification chamber (5).

In some embodiments, the CFB reactor is configured such that the inlet (1c) for fluidizing gas from the intermediate char gasification chamber (9) is positioned below i.e. upstream all inlets (1a) for carbonaceous material into the pyrolysis reaction chamber (1).

According to the present application is also provided a process for manufacturing a product gas having a desirable heating value from a carbonaceous material, comprising

- a first process step where the carbonaceous material is introduced into a first pyrolysis reaction chamber in which are flowing a fluidization gas having a low O_2 content and hot inert recirculating particles, and in which the temperature T_1 is between 400 and 850^oC, producing a product gas which carries partly converted particles i.e. char and recirculating bed particles out of the first process step,

- a second process step where the product gas from the first step is separated from the recirculating and partly converted char particles, where the product gas exits the process while the separated char particles and bed particles enter a third process step

- a third process step, conducted in a primary char reactor, where carbonaceous material remaining in the separated char is subjected to a decomposing oxidation treatment in a fluidized bed at a temperature T_2 between 600 and 850^oC, producing a product gas which is withdrawn from the upper part of the primary char reactor and which product gas, fully or primarily, enters the first process step, together with a fraction of fine entrained particles, while bed particles from the lower part of the primary char reactor are transferred to a fourth process step, and

- a fourth process step, where remaining char is subjected to a second decomposing oxidation treatment in a fluidized bed at a temperature T_3 between 600 and 850^{0}C, producing a product gas which, together with recirculating particles, exits the fourth step and enters the first process step as a fluidization gas,

wherein the gas retention time (t_{10}) in the fluidized bed in the fourth process step is larger than the gas retention time (t_{11}) in the fluidized bed of the third process step ($t_{10}>t_{11}$).

In some embodiments, the first process step is conducted in an atmosphere having a low content of O2, typically <1% or less than 5%.

According to an embodiment of the process, the retention time t_{10} > 1.2 t_{11}- and preferably > 1.5 t_{11}.

According to an embodiment of the process, the temperature T_2 of the third process step and the temperature T_3 of the fourth process step differs with less than 10^{0}C, i.e. $T_3 - T_2 < 10^0$C, normally $T_3 - T_2 < 5\,^0$C.

According to an embodiment of the process, the temperature T_1 is between 400 and 750^{0}C, normally between 625 and 775^{0}C, and even more preferably between 720 and 770^{0}C.

According to an embodiment of the process, the temperature T_2 is between 650 and 850^{0}C, normally between 700 and 800^{0}C.

According to an embodiment of the process, the temperature in the first process step is controlled by regulating the flow of fluidization gas into the fourth process step which to the major part determines the flow of fluidization gas and recirculated particles into the first process step.

According to an embodiment of the process, at least 95 wt% of the bed material in the third process step is inert particle material while at most 5 wt% of the material is carbonaceous material in the form of char.

According to an embodiment of the process, the carbonaceous material fed to the pyrolysis reactor as fuel has a content of ashes above 1% by weight and might have an ash content between 5-50% by weight.

In some embodiments, the carbonaceous material used as fuel has a high content of greater than 0.2% by weight or greater than 0.3% by weight potassium (K), chlorine (Cl) and/or phosphor (P) including in some cases, for example cereal straw, rice straw, and related grain cleaning waste streams; residues from further crops including sugar cane, sorghum and beets, maize, potato, nuts, tea, cotton, olive, wine and oil palms, Algaes – eg. including sea weed, and potential further marine/aquatic derived organic material; energy crops such as grasses - incl. eg. Miscantus - and short rotation forest based on fast growing wood like Willow and Poplar; Crops having an elevated content of salt due to e.g. growth in proximity with salty water or having other contact with salty water; residues from meat production industry such as meat and bone meal; animal manure including dewatered manure slurry; Municipal and industrial organic waste, including organic fractions derived from such streams, sewage sludge, etc.; energy containing residues such as fiber and lignin products from processing wood and raw organic products such as those mentioned above by means of e.g. hydrolysis, extraction and fermentation etc. In some embodiments any of the above listed carbonaceous material may be used as fuel, regardless of potassium (K), chlorine (Cl) and/or phosphor (P) content.

Figure 1 shows an embodiment of a CFB reactor according to the present invention and illustrates how the units of the CFB reactor can be connected. The figure shows a first reaction chamber 1 provided with an inlet 1a through which inlet 1a carbonaceous material is fed through a conduit 2. The first reaction chamber 1 further comprises an outlet 1b for particle loaded product gas, an inlet 1c for fluidization gas and an inlet 1d for product gas from a primary char gasification chamber 5. Said fluidization gas added thorough inlet 1c may be supplemented by the addition of more fluidization gas added through one or more nozzles providing for a satisfying distribution of gas and particles in the bottom part of first reaction chamber 1.

Generally, embodiments of CFB reactors according to the present invention comprise a first reaction chamber 1 wherein carbonaceous material is pyrolysed due to contact with hot recirculating particles. That the carbonaceous material is pyrolysed means that the material is decomposed due to heating and not due to oxidation; pyrolysis is an endothermic process requiring addition of heat. The hot circulating particles transporting heat to the first reaction chamber 1 is normally sand but might be any inert particulate material being adequately resistant to wear.

A feed of carbonaceous material is fed to the first reaction chamber 1 through a conduit 2 and an inlet 1a; the carbonaceous material can be any carbonaceous material such as organic material, coal or products based on petroleum but normally the carbonaceous material is an organic material such as straw or other vegetable waste, soft lignocellulosic biomass such as agricultural residues, manure, household rubbish, dried wastewater, dried animal remains or other dried carbonaceous waste products, optionally mixed with inorganic material

The first reaction chamber 1 has a supply of fluidizing gas in the bottom of the chamber which fluidizing gas provides a fluid bed for reaction and transport of particles in the first reaction chamber, the particles are transported from the bottom of the chamber to a top outlet 1b of the first reaction chamber 1. Typically, the atmosphere in the first reaction chamber 1 is kept low in oxygen in order to reduce the occurrence of oxidizing reactions according to which the carbonaceous material partly ends up as CO_2, and H_2O, i.e. producing heat instead of combustible products. Low oxygen content favors pyrolysis i.e. heat decomposition of the carbonaceous material and normally, the oxygen content in the atmosphere of the first reaction chamber 1 is very low. For example, the oxygen content in chamber 1 is typically less than 1%, or less than 5%. In some embodiments, fluidizing gas is provided primarily from the intermediate char gasification chamber 9 in which chamber char oxidizing reactions occur which produce heat and which reduce oxygen content of the product gas leaving the chamber 9. In some embodiments, some supplemental fluidizing gas may also be added directly to chamber 1.

The optimum temperature in the first reaction chamber 1 depends on what kind of carbonaceous material is being gasified and also the purpose of the product gas and residual ash/solid products. It is typically advantageous to choose a temperature in the first reaction chamber 1 which is sufficient to make the carbonaceous material decompose to a high degree while the temperature should not be high enough to cause agglomeration of the decomposing material and recirculating bed material. Moreover, environmentally problematic and therefor unwanted polyaromatic hydrocarbons (PAH) tend to be produced at high pyrolysis temperature. Normally if the carbonaceous material is a usual organic material, the mean pyrolysis temperature will be advantageous between 400 and 800 ºC. For biofuels material such as straw the temperature will more typically be between 620-700ºC and for very low heating value fuels such as anaerobically digested and dewatered manure from farming animals and such as pre treated sewage sludge, the temperature will more typically be between 500-600ºC. Even lower pyrolysis temperatures can be chosen e.g. for the purpose of producing bio oil and/or bio char.

The temperature in the first reaction chamber 1 is during operation normally controlled mainly by adjusting air flow into the intermediate char gasification chamber 9 and/or by adjusting the total amount of particles in the gasifier. During initial start up the reaction chambers might be heated to temperature of operation by the use of extra burners - and/or after such initial heating also by adding fuel and air/oxygen to e.g. the first reaction chamber 1.

When the product gas carrying particles of char and recirculating particles leaves the first reaction chamber 1 through outlet 1b, the product gas via one or more conduits 3 enters into one or several parallel separators 4 via inlets 4a, the product gas, together with a fine fraction of the particles, leaves the separator 4 through an outlet 4c entering a conduit 18 and the separated particles exits the separator 4 through an outlet 4b entering a conduit 14. The conduit 14 transports the particles to the bottom of a char gasification chamber 5 where the particles are received in a fluid bed 11. The purpose of the separators 4 is to separate the product gas from the main part of the entrained particles as this main part of the particles have to be conveyed to the primary char gasification chamber 5.

The particle separation can be performed using any type of particle separator such as dynamic separators, e.g. turn chamber- , labyrinth, and cyclone separators, or barrier filters, e.g. high temperature bag filters, porous ceramic filters or granular bed type filters, including combinations of the mentioned separators. According to one embodiment the product gas from the first reaction chamber is first cleaned in a primary dynamic separator and thereafter in a secondary, more effective type separator. The re-circulation of particles to the char gasification chamber 5 is in this case primarily performed from the first mentioned primary dynamic separator. The secondary separator may e.g. be just a more efficient cyclone separator or a highly efficient barrier filter.

Normally, the conduit 14 transporting particles from a separator to the primary char gasification chamber 5 will be provided with means or so constructed that gas is prevented from rising from the primary char gasification chamber 5 through the conduit 14 and enter into the separator.

Generally, as much as 70-80% of the organic part of the carbonaceous material is released as gas during pyrolysis and as much as 20-30% of the organic part of the carbonaceous material remains in solid form in char particles. The energy remaining in the char typically constitutes around 30-40% of the total energy content of the original carbonaceous fuel material. Char particles are oxidized at the temperatures prevailing in the char gasification chamber by introduction of a gasification agent. Where oxygen is directly added, the oxidation reaction produces a partially combustible gas, is exothermic and increases temperature in the char gasification chamber. However endothermic, steam-based char conversion reactions can also be conducted which produce a partially combustible gas but which serve to lower temperature. The double purpose of the primary char gasification chamber 5 is to heat up the inert re-circulating particles and to optimize char conversion i.e. to optimize recovery of combustible gas from the carbonaceous particles which have been previously subjected to pyrolysis. A fine fraction of the char particles will be lost in the separator section but normally at least 80% will be transferred from the separator section to the primary char gasification chamber 5.

The primary char gasification chamber 5 comprises an inlet 5a for pyrolysed and inert recirculating particles, it also comprises an inlet 5b for fluidizing gas which in the figure is supplied via a conduit 6 in the lower part of the primary char gasification chamber 5. The fluidizing gas is normally supplied to the primary char gasification chamber 5 through many nozzles(not shown) and/or other air distributing means assuring a flow pattern suitable for maintaining a fluid bed in the chamber. Normally, the primary char gasification chamber 5 has a bubbling fluidized bed in the lower part. Normally, the gasification agents also serves as the fluidizing gas and is a mixture of mainly air and some steam (H_2O) which will increase the temperature overall- but the char gasification chamber may also have one or more more-or-less separate inlets for liquid gasifying agents such as water– which will more effectively than steam lower the temperature in the chamber.

The primary char gasification chamber 5 comprises an outlet 5d in the upper part of the char gasification chamber 5 for gas and an outlet 5c for particles in the bottom part of the char gasification chamber 5. The outlet 5c opens into a particle return conduit 7 which particle return conduit 7 opens into an intermediate char gasification chamber 9 through inlet 9a.

The mean temperature in the primary char gasification chamber 5 will normally be at least 50ºC higher than the temperature in the first reaction chamber 1, which will normally mean that the particles entering the first reaction chamber 1 via the inlet 1c is at least 50ºC higher than the desired operating temperature in the first reaction chamber 1. In the case of using high alkaline fuels, the temperature in the primary char gasification chamber 5 is normally kept below 770ºC.

The atmosphere in the primary char gasification chamber 5 contains oxygen which results in that exothermic oxidizing reactions take place in the primary char gasification chamber 5. The oxygen content in the atmosphere of the primary char gasification chamber 5 during operation is high enough to decompose most of the char material by oxidation. However, in typical embodiments, the oxygen content in the added gasification agent is maintained well below sub-stoichiometric levels, meaning that there is insufficient oxygen to fully oxidize all of the char material added to the primary char gasification chamber 5 via inlet 5a. During operation a fluidized bed 11 of particles is provided in the lower part of primary char gasification chamber 5. The volume of this fluidized bed 11 which is normally a bubbling fluid bed is defined as the volume present above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the surface of the same fluidized bed. The height h_{11} of the fluid bed 11 is indicated on the figure. The height h_{11} of the fluidized bed 11 can be evaluated and maintained on a desired level by measuring differential pressures in the fluidized bed and by comparing these pressures to pressures measured in the freeboard volume 13. Said freeboard volume 13 is above the volume of the fluidized bed 11 and this freeboard volume 13 contains gas and particles being too fine to remain in the bubbling bed and instead are carried with the gas to the outlet 5d and into the conduit 15. After the gas has left the char gasification chamber 5, the gas can either enter the first reaction chamber 1 through the conduit 17 and the inlet 1d or part of the gas or all the gas can leave the CFB reactor through conduit 16.

The particles leaving the primary char gasification chamber 5 through the bottom exit 5c enter the intermediate char gasification chambers 9 through inlet 9a. The intermediate char gasification chamber 9 further comprises an inlet 9b for adding fluidizing gas in the lower part of the reactor 9 and this way a fluidized bed 10 is formed in the intermediated char gasification chamber 9. The added fluidizing gas is typically mainly air but might also be other gasification agents such as O_2 and/or steam (H_2O) while a further gasification agent might be liquid water which might be introduced through separates inlets. Also, the intermediate char gasification chamber 9 comprises an outlet 9c for produced gas carrying particles from the upper part of the chamber 9 which outlet 9c opens into a conduit 8 having at least one outlet to the lower part of the first reaction chamber 1. I.e. the intermediate char gasification chamber 9 provides fluidizing gas to the first reaction chamber 1 and as the gas produced in the intermediate char gasification chamber 9 is deprived of oxygen it is not necessary to add a major amount of further oxygen depleted fluidizing gas to the bottom of the first reaction chamber 1 and in particular the use of inert gas such as N_2 as fluidizing gas can be avoided.

During normal operation most of the particles entering the intermediate reactor 9 through the inlet 9a are transported upwards to the outlet 9c Exceptions are char particles being converted to gas within the reaction chamber 9 and that surplus particles constituting an ash stream might be removed from the bottom of the chamber 9.

The volume of the fluidized bed 10 is defined as the volume above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the center of the outlet 9c for produced gas and particles in the upper part of the intermediate char gasification chamber 9, the height h_{10} of this fluidized bed 10 being indicated in the figure.

The CFB reactor is constructed in such a way that it is possible to make the height h_{10} of the second fluidized bed 10, which is defined by the inlet of fluidized air and the outlet for gas and particles, larger than the height h_{11} of the first fluidized bed 11 in the char gasification chamber (5).

Normally, less than 30% of the char decomposition takes place in the intermediate char gasification chamber 9 and more than 70% of the char decomposition takes place in the primary char gasification chamber 5. .This and also at least a minimum (clear) extent of benefits of including the intermediate reactor 9 is achieved by adding typically between 70% to 95% of the total mass flow of gasification agents to the primary char reactor 5 while adding the rest, i.e. between 30% and 5% to the intermediate reactor.

In order to free the energy remaining in the char which constitutes a considerable part of the total energy of the carbonaceous fuel material fed to the CFB reactor, it is desirable to operate the primary char gasification chamber 5 at as high a temperature as possible without risking agglomeration of the particles in the fluid bed. If the highest allowable temperature is obtained in the primary char gasification chamber 5 it will be a problem that the temperature in the downstream fluid bed i.e. the fluid bed in the intermediate char gasification chamber is 10-20^{o}C higher than the temperature in the char primary gasification chamber 5 as this can cause agglomeration of the material and result in shutting down of the CFB reactor or require a lower temperature in the primary char gasification chamber

By adjusting the height of the fluid beds in respectively the primary char gasification chamber 5 and the intermediate char gasification chamber 9, it is possible to increase gas and particle retention times in the intermediate char gasification chamber 9. By increasing these retention times, slower, steam-based endothermic reactions will be better allowed to take place in the intermediate char gasification reactor 9 supplemental to the dominating and faster exothermic reactions. Steam-based endothermic reactions are also promoted by use of a higher steam to oxygen ratio in the gasification agent introduced to the intermediate char gasification chamber compared with that used in the primary char gasification chamber. For the most typical example of adding oxygen by adding air, suitable steam to air mass flow ratios in the intermediate chamber is higher than the corresponding ration in the primary char gasification chamber and typically at least 0.05 (i.e. > 5% steam) may be as high as 0.1 or 0.2 or 0.5. By giving the endothermic reactions time to occur, the mean temperature in the intermediate char gasification reactor will become lower and it will be possible to maintain a temperature in the intermediate char gasification reaction which is less than 10°C and preferably less than 5°C higher than the temperature in the primary char gasification chamber 5. This also means it will be possible to increase the decomposition of the char in the intermediate reactor 9 by increasing the volume of this chamber without having a problematic increase in temperature of approximately 10-20°C compared to the temperature in the primary char reactor 5.Providing the said extra gas retention time in the intermediate reactor and this way converting more char by means of slow endothermal reactions is also a better solution for avoiding said problematic temperature increase than providing e.g. the same cooling effect by just adding extra badly converted steam or water.

The cross-section of the intermediate char gasification chamber is normally dimensioned to typically - and at approximately the same resulting superficial fluidization velocity - consume a certain amount of gasification agent compared to the mass flow of gasification agent added to the primary reaction chamber 1. The fluidization gas travelling through the intermediate char gasification chamber 9 carries heated inert particles and has to be conditioned to adequately low oxygen content and although it would be possible to increase the retention time by reducing the flow of fluidization gas in the intermediate char gasification chamber, the minimum flow of fluidization gas is primarily defined by the need for transport of particles through the chamber.

The product gas typically has a higher heating value between 4-8 MJ/Nm^3. This range of heating values is typical for mainly air blown gasifiers, while higher heating values can be obtained by using a gasification agent that has a higher content of oxygen compared to Nitrogen..

The invention also relates to a process comprising the following steps:

1) Carbonaceous material is introduced in a first reaction chamber in a fluidization gas having a low content of O_2 and hot inert recirculating particles, the temperature T_1 is between 400 and 850^{0}C. The carbonaceous material is subjected to thermal decomposition i.e. pyrolysis. All material i.e. char particles and inert heat transporting particles is by the product gas carried to a top outlet in the first reaction chamber through which the product gas and the particles exits the first process step. There might be an outlet for extraction of ashes e.g. including oversize particles from the bottom of this pyrolysis reaction chamber 1.

2) The product gas carrying particles enters a separation zone where the product gas is separated from the particles, the product gas which has an increased heating value relative to the supplied fluidization gas is either collected or taken directly to consumption, while the separated particles are transferred to a char gasification chamber.

3) The remaining carbonaceous material i.e. the char particles is subjected to a decomposing treatment in a fluidized bed at a temperature T_2 between 600 and 850^{0}C. The product gas from this process step is withdrawn from the char gasification chamber and enters the first process step e.g. together with a fraction of entrained fine particles. A part of the product gas might be withdrawn from the process instead of entering the first reaction chamber. The particles other than particles transferred with product gas or removed for purposes of circulation control are transferred to a fourth process step.

4) The still remaining carbonaceous material is subjected to a second decomposing treatment in a fluidized bed at a temperature T_3 between 600 and 850^{0}C. A product gas as well as recirculating particles exits the fourth step and enters the first process step as fluidization gas and heat carrying particles. . The gas retention time (t_{10}) in the fluidized bed in the fourth process step is larger than the gas retention time (t_{11}) of in the fluidized bed of the third process step ($t_{10}>t_{11}$). In some embodiments, product gas from the fourth

process step enters the first process step as fluidization gas below the entrance for carbonaceous material in the first reaction chamber.

The description of embodiments provided is representative only and not intended to limit the scope of the inventions as defined by the claims.

Claims:

1. A circulating fluidized bed (CFB) reactor for thermal processing of added carbonaceous material, comprising:

- a first pyrolysis reaction chamber (1) wherein added carbonaceous material is pyrolysed due to contact with hot recirculating particles, which first reaction chamber (1) has an inlet (1a) for carbonaceous material, an inlet (1c) for fluidizing gas, and an outlet (1b) for product gas in the upper part of the first reaction chamber (1) which product gas carries carbon containing char particles and recirculating inert particles,

- one or more separators (4) having an inlet (4a) through which the product gas carrying particles from the first reaction chamber (1) is received, and an outlet (4b) through which the particles leave each separator and enter into a primary char gasification chamber (5) via one or more conduits (14),

- said primary char gasification chamber (5) comprising an inlet (5a) for pyrolysed and recirculating particles, an inlet (5b) for fluidizing gas (6) in the lower part of the primary char gasification chamber (5), an outlet (5d) in the upper part of the primary char gasification chamber (5) for produced gas and an outlet (5c) for particles in the lower part of the primary char gasification chamber (5) opening into a particle return conduit (7) which particle return conduit (7) opens into an intermediate char gasification chamber (9), and

- said intermediate char gasification chamber (9) comprising an inlet (9a) for particles from the primary char gasification chamber (5) and an inlet (9b) for a fluidizing gas e.g. gas containing O_2/H_2O in the lower part of the reactor (9), and further comprising an outlet (9c) for produced gas carrying particles from the upper part of the chamber (9) which outlet (9c) opens into a conduit (8) having at least one outlet to the lower part of the first reaction chamber (1) and which provides fluidizing gas to the first reaction chamber (1).

2. A CFB reactor according to claim 1, wherein the inlet (1c) for fluidizing gas from the intermediate char gasification chamber (9) is positioned below i.e. upstream the inlet (1d) for gas from the fluidized bed primary char gasification chamber (5).

3. A CFB reactor according to claim 1, wherein an outlet for ashes is provided in one or more of the separators (4) and/or in the bottom of the intermediate char gasification chamber (9).

4. A CFB reactor according to claim 1, wherein the cross-sectional area of the intermediate char gasification reactor is at least 50 % smaller than the cross-sectional area of the primary char gasification chamber (5).

5. A CFB reactor according to claim 1, wherein the inlet (1c) for fluidizing gas from the intermediate char gasification chamber (9) is positioned below i.e. upstream all inlets (1a) for carbonaceous material into the pyrolysis reaction chamber (1).

6. A CFB reactor according to claim 1, wherein the reactor is configured such that the top of the intermediate char gasification chamber is placed at a level that is intermediate between the levels of the top and bottom of the primary char gasification chamber.

7. A CFB reactor according to claim 1 wherein the reactor is configured such that the top of the intermediate char gasification chamber (9) is placed at a level that is higher than that level of the primary char gasification chamber (5) at which the majority of fluidizing gas is introduced.

8. A CFB reactor according to claim 1, wherein the reactor is configured such that greater than 50% of the volume of the intermediate char gasification chamber is placed at a level beneath the bottom of the primary char gasification chamber and beneath the bottom of the pyrolysis chamber.

9. A CFB reactor according to claim 1, wherein during operation a first fluidized bed (11) of particles is provided in the primary char gasification chamber (5), the volume of said first fluidized bed (11) is defined as the volume present above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the surface of the same fluidized bed, above the volume of the first fluidized bed (11) is a lower density freeboard volume (13) containing gas and entrained fine particles,

10. A CFB reactor according to claim 1, wherein during operation particles are transported through the intermediate char gasification chamber (9) forming a second fluidized bed (10) of particles where the volume of said second fluidized bed (10) is defined as the volume above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the center of the outlet (9c) for produced gas and particles in the upper part of the intermediate char gasification chamber wherein the height (h_{10}) of the second fluidized bed (10) in the intermediate char gasification chamber (9) is larger than the height (h_{11}) of the first fluidized bed (11) in the primary char gasification chamber (5).

11. A CFB reactor according to claim 1, wherein during operation particles are transported through the intermediate char gasification chamber (9) forming a second fluidized bed (10) of particles where the volume of said second fluidized bed (10) is defined as the volume above the level of adding the fluidizing gas at the bottom of the fluidized bed and up to the center of the outlet (9c) for produced gas and particles in the upper part of the intermediate char gasification chamber wherein the pressure difference between the bottom and top of the primary char gasification chamber (5) is smaller than between the bottom and top of the intermediate char gasification chamber (9).

12. A CFB reactor according to claim 1 further comprising nozzles through which fluidizing gas may be introduced located within the bottom 15% of the pyrolysis chamber.

13. A process for manufacturing a product gas having a desirable heating value from a carbonaceous material, comprising

- a first process step where the carbonaceous material is introduced into a first pyrolysis reaction chamber in which are flowing a fluidization gas having a low O_2 content and hot inert recirculating particles, and in which the temperature T_1 is between 400 and 850^{0}C, producing a product gas which carries partly converted particles i.e. char and recirculating bed particles out of the first process step,
- a second process step where the product gas from the first step is separated from the recirculating and partly converted char particles, where the product gas exits the process while the separated char particles and bed particles enter a third process step

- a third process step, conducted in a primary char reactor, where carbonaceous material remaining in the separated char is subjected to a decomposing oxidation treatment in a fluidized bed at a temperature T_2 between 600 and 850^{0}C, producing a product gas which is withdrawn from the upper part of the primary char reactor and which product gas enters the first process step, together with a fraction of fine entrained particles, while bed particles from the lower part of the primary char reactor are transferred to a fourth process step, and

- a fourth process step, where remaining char is subjected to a second decomposing oxidation treatment in a fluidized bed at a temperature T_3 between 600 and 850^{0}C, producing a product gas which, together with recirculating particles, exits the fourth step and enters the first process step as a fluidization gas,

wherein the gas retention time (t_{10}) in the fluidized bed in the fourth process step is larger than the gas retention time (t_{11}) in the fluidized bed of the third process step ($t_{10}>t_{11}$).

14. A process according to claim 13, wherein t_{10} > 1,2 t_{11}, and preferably > 1.5 t_{11}.

15. A process according to claim 13, wherein the temperature T_2 of the third process step and the temperature T_3 of the fourth process step differs with less than 10^{0}C, i.e. $T_3 - T_2 <$ 10^{0}C, normally $T_3 - T_2 < 5$ ^{0}C.

16. A process according to claim 13, wherein the temperature T_1 is between 400 and 800^{0}C, normally between 625 and 775^{0}C.

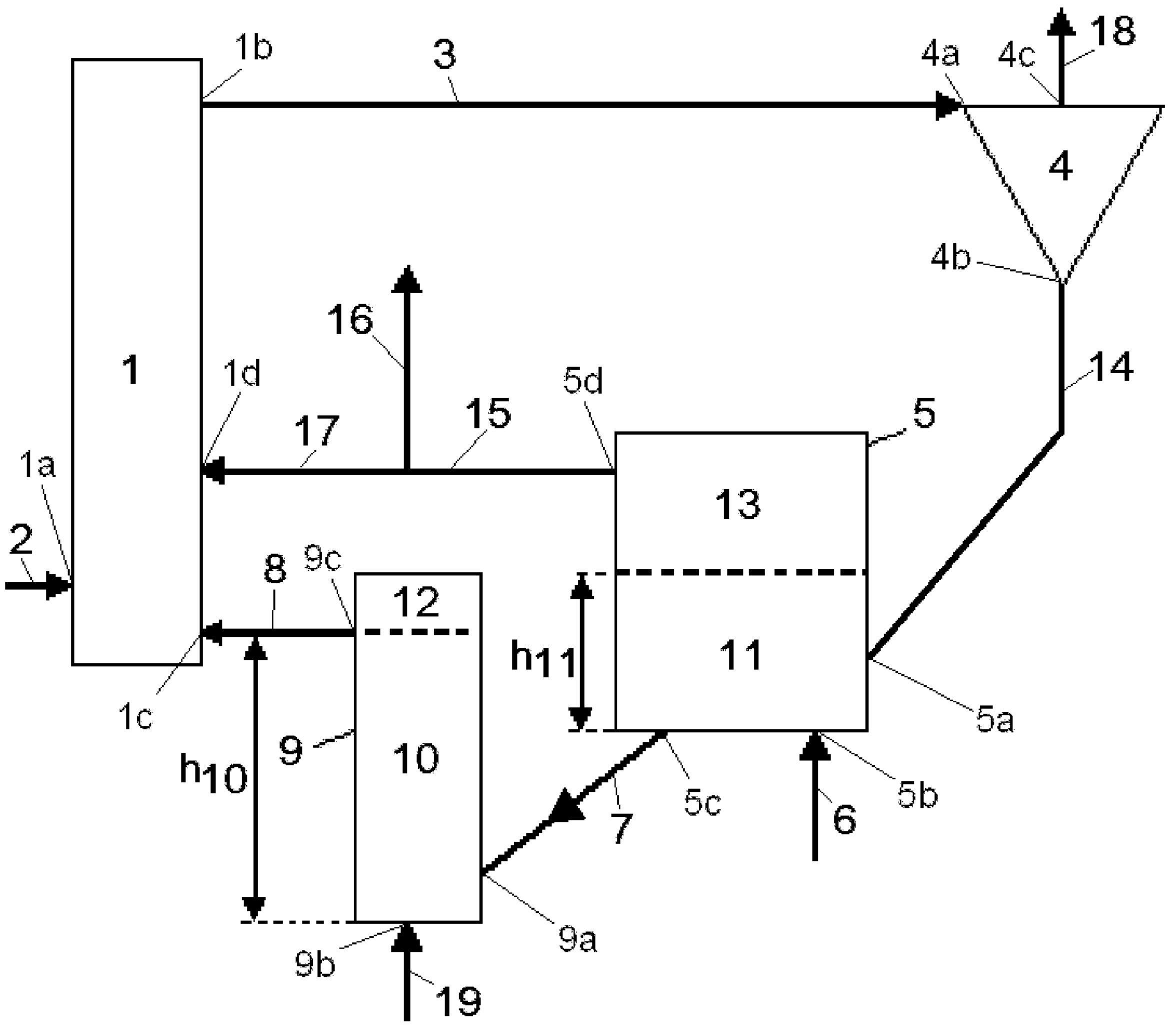
17. A process according to claim 13, wherein the temperature T_2 is between 650 and 800^{0}C, normally between 700 and 800^{0}C.

18. A process according to claim 13, wherein the temperature in the first process step is controlled by regulating the flow of fluidization gas into the fourth process step which determines the flow of fluidization gas and recirculating particles into the first process step.

19. A process according to claim 13, wherein at least 95 wt% of the bed material in the third process step is inert particle material while less than 5 wt% of the material is remaining carbonaceous material.

20. A process according to claim 13, wherein the carbonaceous material comprises any one or more of cereal straw, rice straw, related grain cleaning waste streams; residues from crops including sugar cane, sorghum, beets, maize, potato, nuts, tea, cotton, wine, olive and oil palms; Algaes – eg. including sea weed; energy crops including grasses, including eg. Miscantus; residues from short rotation forest crops based on fast growing wood including Willow and Poplar; Crops having an elevated content of salt due to e.g. growth in proximity with salty water or having other contact with salty water; residues from meat production industry including meat and bone meal; animal manure including dewatered manure slurry; Municipal and industrial organic waste, including organic fractions derived from such streams; sewage sludge; or energy containing residues such as fiber and lignin products from processing wood and raw organic products.

21. A process according to claim 13, wherein during operation the pressure difference between the bottom and top of the primary char gasification chamber (5) is smaller than between the bottom and top of the intermediate char gasification chamber (9).


1b
3
4a
4c
18
4
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1d
5d
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14
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2
9c
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12
h11
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Fig. 1

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2013/050242

A. CLASSIFICATION OF SUBJECT MATTER
INV. C10J3/48 C10J3/54 F23C10/10
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)
C10J F23C

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 practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	WO 2011/153568 A1 (UNIV WIEN TECH [AT]; PROELL TOBIAS [AT]; SCHMID JOHANNES [AT]; PFEIFER) 15 December 2011 (2011-12-15) page 12, line 6 - page 20, line 19; figures 1, 4 -----	1-21
X	US 2010/221152 A1 (SUDA TOSHIYUKI [JP] ET AL) 2 September 2010 (2010-09-02) paragraph [0044] - paragraph [0050]; figure 1 -----	1-21
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 September 2013	04/10/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Iyer-Baldew, A

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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