

"PROCESSES AND SYSTEMS FOR THERMAL TREATMENT OF PARTICULATE MATERIALS"

Cross-Reference to Related Applications

[0001] This application claims priority to Australian provisional patent application no. 2023903476, filed on 30 October 2023, the disclosure of which is incorporated herein in its entirety.

Technical Field

[0002] The present disclosure generally relates to the thermal treatment of particulate material. In particular, the disclosure relates to thermal treatment involving activation and compaction of a particulate material to increase its propensity to undergo a target chemical reaction at an elevated temperature.

Background

[0003] Various processes are known for the thermal treatment of particulate materials across various industries and for various purposes, limited examples of which include the direct reduction of iron ore fines in iron and steel making, and the calcination and clinkering of raw meal for cement production. However, many, if not most, of these processes suffer from significant process and thermal inefficiencies. These processes are furthermore notorious for causing emissions of environmentally harmful gases, with iron and steel and cement production industries being responsible for about 6-8% and 8% of global carbon dioxide (CO₂) emissions respectively.

[0004] With an increasing demand for critical materials and an emphasis on decarbonisation, there is a need across various industries for a process enabling the thermal treatment of particulate material which is not only sustainable, but also allows for the efficient capture of unavoidable emissions and at least the optionality to electrify.

[0005] Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present disclosure as it existed before the priority date of each of the appended claims.

Summary

[0006] According to an aspect of the present disclosure, there is provided a process for the thermal treatment of a particulate material, the process including:

introducing the particulate material into a vertical first reactor segment, the particulate material introduced into the first reactor segment at a top end in order that the particulate material flows under gravity through the first reactor segment

heating the particulate material from outside the first reactor segment to activate the particulate material

compacting the hot activated particulate material to form agglomerates.

[0007] The process may include, prior to the compacting of the hot activated particulate material, additional particulate materials are added to the hot activate particulate material. The additional particulate material may include, for example, materials such as flow aids, or materials that are not required to be processed in the first reactor segment, or materials prepared in a different oxidation/reduction environment to the environment of the first reactor segment. Adding such additional materials to be compacted with those processed in the first reactor segment may advantageously affect the processing conditions. For example, adding such additional particles into the compaction system at a defined temperature can enhance control of the compaction process temperature, such as to mitigate or to activate phase changes of the particles or chemical reactions within the agglomerate as it is formed, or later in the second reactor segment described below. The additional materials may be added at ambient temperature, at a lower temperature than the hot activated particulate material from the first reactor segment, or at a higher temperature than the hot activated particulate material.

[0008] The process may further include:
introducing the formed agglomerates into a top end of a vertical second reactor segment to form a packed bed in the second reactor segment
heating the agglomerates in the packed or moving bed to induce a target reaction within the agglomerates as the agglomerates move through the packed bed
discharging the reacted agglomerates from a bottom end of the second reactor segment.

[0009] Reference to particulate material, or particulate feed material, in the context of the present disclosure, may refer to one or any combination of: mined limestone or dolomite; synthetic calcium and magnesium carbonates; a supplementary or substitute cementitious material (SCM); raw or cement meal; a metalliferous ore and/or concentrate; and biomass.

[0010] Reference to “activate”, in the context of the present disclosure, refers to the at least partial metallisation, partial decomposition, gasification, volatilization, calcination, reduction, and/or oxidation of at least a constituent of the particulate material to form hot activated particulate material, such that the hot activated particulate material is in a solid state which exhibits a comparatively increased propensity to undergo the target solid state reaction at an elevated temperature.

[0011] Reference to the “target reaction”, in the context of the present disclosure, refers to a physical and/or chemical process producing a product at least partially through an atomic transport process between constituent particles of the agglomerates.

[0012] By non-limiting examples, the particulate material processed according to the process of any of the preceding paragraphs, or described below, may be or include: raw or cement meal for use in making Portland Cement clinker; limestone for use in making lime; a combination of limestone and kaolinite clay for use in making an SCM, the combination optionally including an additive or additives; magnesite for use in making magnesia or other refractory material; or a combination of SCM particles and Portland Cement particles.

[0013] The reacted agglomerates may be a densified product or a porous product.

[0014] An off-gas may be discharged from the first reactor segment from an outlet disposed at a top end of the first reactor segment. The off-gas may comprise a gas product from the activation of the particulate material. The off-gas may be passed through a separator to at least partially separate out entrained solid particles in the off-gas to produce a cleaned off-gas. The separated solid particles may be reintroduced into the first reactor segment at the top end. The separator may comprise one or more cyclones and/or filters in fluid flow connection with the outlet disposed of the first reactor segment.

[0015] Heating the particulate material from outside the first reactor segment may be by means of a first heating system adjacent to and disposed along a length of the first reactor segment. It will be appreciated that activation of the particulate material may be exothermic, in which case heat from activation of the particulate material may contribute to the heating of the particulate material in the first reactor segment.

[0016] Heating the agglomerates in the packed bed in the second reactor segment may involve one or more of: heating from outside the second reactor segment; heating by means of a combustion reaction within the second reactor segment; heating by means of injecting a hot gas into the second reactor segment and passing the hot gas through the packed bed of agglomerates; and an electric smelting process. The second reactor segment may comprise a second heating system adjacent to and disposed along a length of the second reactor segment for heating the agglomerates in the packed bed from outside the second reactor segment.

[0017] The first heating system and/or the second heating system may comprise electric heating elements, non-limiting examples of which include induction and resistive heating elements. One or both of the first heating system and the second heating system may comprise an electric smelting furnace. Where the first heating system and/or the second heating system comprise electric heating elements, the electric heating elements may be powered by a renewable energy source and/or an

electrical grid. Where the electric heating elements are powered by an electrical grid, the first heating system and/or the second heating system may be used as a demand side mechanism for balancing the electrical grid.

[0018] The first heating system and/or the second heating system may be a furnace segment in thermal connection with its associated reactor segment, wherein heat is generated from a combustion reaction or from dissipation of electric power within the material, or from both combustion and electric dissipation. The combustion reaction may be oxyfuel combustion using a synthesis gas or gases and a source of oxygen, including but not limited to oxygen gas. The combustion reaction may act to form a gas product as a furnace segment flue gas. The furnace segment may be in thermal connection with its associated reactor segment by a thermally conductive element. The thermally conductive element may be a wall of the associated reactor segment.

[0019] The heating from dissipation of electric power within the second reactor segment may use an electric smelting furnace configured to take advantage of the electrical resistivity of a material, preferably being a molten material, where such molten material is prepared either in the first reactor segment or by a backflow of material from the second reactor segment, or both.

[0020] The combustion reaction within the second reactor segment may be achieved by introducing a feed gas into the second reactor segment, the feed gas comprising one or any combination of a synthesis gas or gases; a source of oxygen, including but not limited to oxygen gas or air; and a source of hydrogen including but not limited to hydrogen gas. Where the feed gas comprises a combination of a synthesis gas or gases and a source of oxygen, the synthesis gas or gases and source of oxygen may be introduced separately into the second reactor segment so that on mixing, oxyfuel combustion heats the packed bed of agglomerates. The oxyfuel combustion may be flameless. The feed gas may be introduced into the second reactor segment at an elevated temperature.

[0021] It will be appreciated that the combustion reaction within the second reactor segment and/or the target reaction may form a gas product as a second reactor segment flue gas.

[0022] The off-gas from the first reactor segment, the furnace segment flue gas, the second reactor segment flue gas, and/or from a precombustion capture process of a gasifier product may comprise CO₂ and/or H₂O. Where the furnace segment flue gas and/or the second reactor segment flue gas and/or the off-gas from the first reactor segment comprises CO₂, the process may include capturing the CO₂ in one or more of the furnace segment flue gas, the second reactor segment flue gas and the first reactor segment off-gas at a carbon capture facility. The carbon capture facility may comprise one or any combination of the following: cooling; gas cleaning; separation of H₂O and/or other impurities; compression or liquefaction; and storage. The gas cleaning and separation processes may contain activated lime or dolime, such as made using the activation process described below. The captured CO₂ may be used in a methanol, substitute aviation gas, and/or hydrocarbon materials production facility.

[0023] The CO₂ released from the first reactor segment flue gas may be from a CO₂ loaded sorbent from a direct air capture facility in which heating releases the CO₂ and generates a sorbent precursor which is processed by compaction and reaction in the second reactor segment to form a product with a composition, particle size, shape, porosity, and surface area appropriate for reuse in the direct air capture facility.

[0024] Where the captured CO₂ is used in a methanol production facility, the source of oxygen to the furnace segment and/or the second reactor segment may be obtained from a methanol electrolyser of the methanol production facility.

[0025] The synthesis gas or gases to the furnace segment and/or the second reactor segment may be formed at a gasification facility. Where the captured CO₂ is used in a methanol production facility, the gasification facility may comprise gasification of a biomass with oxygen obtained from a methanol electrolyser of the methanol production facility. The gasification product from the gasification of the biomass with oxygen

may be cleaned to form the synthesis gas or gases. The gasification process may produce CO₂. The CO₂ from the gasification process may be removed by a pre-combustion capture process or stage, such as a Sorbent Enhanced Water Gas Shift (SEWGS) process, and the hydrogen stream used for oxyfuel combustion. The SEWGS sorbent may contain activated lime or dolime, such as made using the activation process described below.

[0026] The captured CO₂ may at least in part be injected into one or both of the furnace segment and the second reactor segment to regulate a temperature within the furnace segment and/or the second reactor segment.

[0027] The particle size distribution of the particulate material introduced into the first reactor segment is preferably in a range of 150µm to 350µm.

[0028] The process may include fusing the particulate material to produce a particle size distribution in the range of 150µm to 350µm prior to introducing the particulate material into the first reactor segment. Fusing the particulate material may be by means of a cylindrical mill.

[0029] The particulate material may be homogenised prior to introducing the particulate material into the first reactor segment.

[0030] Compacting the hot activated particulate material to form the agglomerates may be performed by a heat-resistant roller press. It will be appreciated that the agglomerates may be any shape, non-limiting examples of cross-sectional or general agglomerate shapes include “pillow”, irregular, rectangular, square, rounded, cylindrical, “cigar”, tablet and polygon shapes. The dimensions of the agglomerates are preferably within a range of 1cm to 10cm. By non-limiting example, the agglomerates may be elongate, and may be generally cylindrical or “cigar” shape having a width or a diameter ranging from 1cm to 3cm and a length ranging from 3cm to 6cm. The hot activated particulate material may be compacted at a linear pressure of

approximately 100 kN/cm² and may be compacted at a pressure of up to 200 kN/cm² to form the agglomerates.

[0031] A residence time of the particulate material in the first reactor segment may be less than 60 seconds, preferably less than 40 seconds, most preferably in a range of 20 to 30 seconds. A residence time of an agglomerate within the packed bed in the second reactor segment may be less than 10 minutes, preferably approximately 5 minutes. It will however be appreciated that the residence time of an agglomerate within the packed bed in the second reactor segment is at least in part dependent on the particulate material, a temperature to which the agglomerates are heated in the second reactor segment and the size of the agglomerates, and therefore the residence time can exceed 60 minutes in certain instances.

[0032] The first reactor segment and/or second reactor segment may operate at a positive gauge pressure.

[0033] The process may include cooling the reacted agglomerates discharged from the second reactor segment to allow for handling and/or transport. Cooling the agglomerates may be carried out by means of a device such as a grate cooler.

[0034] The process may include crushing the reacted agglomerates to form a powder product. Where cooling the agglomerates is carried out by a grate cooler, the grate cooler may comprise rotating spikes, the reacted agglomerates thereby crushed in the grate cooler.

[0035] The particulate material introduced into the first reactor segment may be preheated.

[0036] According to another aspect of the present disclosure, there is provided a system for the thermal treatment of a particulate material, the system including:

a vertical first reactor segment configured to receive the particulate material at a top end thereof in order that the particulate material flows under gravity through the

first reactor segment and a first heating system adjacent to and disposed along a length of the first reactor segment to heat the particulate material flowing through the reactor segment from outside the reactor segment so as to activate the particulate material; and a compactor for receiving and compacting the hot activated particulate material from the first reactor segment to form agglomerates.

[0037] The system may include a mechanism arranged to introduce additional particulate materials to the hot activated particulate material prior to compaction by the compactor. The mechanism may be an injection mechanism arranged to inject the materials directly into the compactor, or arranged to inject the additional materials upstream of the compactor. The mechanism is typically arranged and operable to introduce the additional materials to the hot activated materials before compaction by the compactor. It will be appreciated that a range of mechanisms capable of introducing the additional particulate materials to the activated material, such as by jetting, spraying, pumping, extruding, depositing, and the like, are within the scope of this disclosure.

[0038] The system may include a vertical second reactor segment configured to: receive the agglomerates from the compactor at a top end thereof, the agglomerates forming a packed bed within the second reactor segment; heat the agglomerates in the packed bed to induce a target reaction within the agglomerates as the agglomerates move through the packed bed.

[0039] The reacted agglomerates may be discharged from an outlet of the second reactor segment disposed at a bottom end thereof.

[0040] The second reactor segment may include a discharge system configured to control the rate of movement of the agglomerates through the packed bed in the second reactor segment.

[0041] The second reactor segment may be configured to heat the agglomerates in the packed bed from outside the second reactor segment by one or more of: operating a

second heating system adjacent to and disposed along a length of the second reactor segment; causing a combustion reaction within the second reactor segment; injecting a hot gas into the second reactor segment and passing the hot gas through the packed bed of agglomerates; and electrically smelting the agglomerates.

[0042] The first heating system and/or the second heating system may comprise one or more electrical heating elements. The electrical heating elements may be induction or resistive heating elements. The first heating system and/or the second heating system may comprise an electric smelting furnace.

[0043] The first heating system and/or the second heating system may comprise a furnace segment in thermal connection with its associated reactor segment, wherein heat is generated from a combustion reaction.

[0044] The combustion reaction may be oxyfuel combustion using a synthesis gas or gases and a source of oxygen, including but not limited to oxygen gas. The combustion reaction may act to form a gas product as a furnace segment flue gas. The furnace segment may be in thermal connection with the associated reactor segment by a thermally conductive element. The thermally conductive element may be a wall of the associated reactor segment.

[0045] The target reaction and/or the combustion reaction may produce a gas as a second reactor segment flue gas.

[0046] The first reactor segment and the second reactor segment may be distinct reactors or, alternatively, may be segments of a unitary reactor. The second reactor segment may be in fluid flow connection with the first reactor segment.

[0047] The first reactor segment may be configured to discharge an off-gas from an outlet disposed at a top end of the first reactor segment.

[0048] Activation of the particulate material may act to form the off-gas in the first reactor segment. Where the first reactor segment and the second reactor segment are segments of a unitary reactor and/or are in fluid flow connection, the second reactor segment flue gas may be discharged from the outlet disposed at a top end of the first reactor segment as the off-gas or a part thereof.

[0049] Where the first reactor segment is configured to discharge a gas from an outlet disposed at a top end of the first reactor segment, the system may include a separator in fluid flow connection the outlet disposed at the top end of the first reactor segment so as to receive the off-gas so as to at least partially separate out entrained solid particles. The separator may be configured to reintroduce the separated solid particles into the first reactor segment at the top end. The separator may comprise one or more cyclones and/or filters.

[0050] Where the off-gas, second reactor segment flue gas, furnace segment flue gas, and/or precombustion capture gas comprises CO₂, the system can include a carbon capture facility for receiving any one or more of the off-gas, second reactor segment flue gas and/or furnace segment flue gas separately or in combination. The carbon capture facility may comprise one or any combination of the following systems: cooling; gas cleaning; separation of H₂O and/or other impurities; compression or liquefaction; and storage. The CO₂ from the gasification process may be removed by a pre-combustion capture system, such as a Sorbent Enhanced Water Gas Shift (SEWGS) system, and the hydrogen stream used for the oxyfuel combustion system. The SEWGS system may contain activated lime or dolime, such as made using the activation process described below. The captured CO₂ may be used in a methanol, substitute aviation gas and/or hydrocarbon materials production facility.

[0051] The system may include a gasification facility configured to produce a synthesis gas or gases for use in the combustion reaction in any one or both of the second reactor segment and the furnace segment. The gasification facility may comprise a gasifier configured to gasify a biomass feed with oxygen gas obtained from a methanol electrolyser of the methanol production facility. The gasification facility

may comprise a gas cleaning operation to produce the synthesis gas or gases from the gasified biomass feed. The CO₂ from the gasification process may be removed by a pre-combustion capture system, such as a Sorbent Enhanced Water Gas Shift (SEWGS) system, and the hydrogen stream used for the oxyfuel combustion system. The SEWGS system may contain activated lime or dolime, such as made using the activation process described below.

[0052] The system may include a preheater for preheating the particulate material prior to being received by the first reactor segment.

[0053] The system may include a fusion and/or homogenising facility for fusing the particulate material to produce a particle size distribution in the range of 150µm to 350µm and/or homogenising the particulate material prior to introducing the particulate material into the first reactor segment. The fusion and/or homogenising facility may comprise a cylindrical mill.

[0054] The compactor may be one or more heat-resistant roller presses.

[0055] Where the first heating system and/or second heating system comprises one or more electrical heating elements, the system may include a renewable power facility for powering the electrical heating elements. The renewable power facility may receive power from a renewable energy source or may comprise a renewable energy source. The renewable power facility may include a power storage arrangement, the electrical heating elements powered from the renewable energy source indirectly via the power storage arrangement. The power storage arrangement may comprise vanadium redox flow battery cells charged from the renewable energy source.

[0056] The system may include a cooling facility configured to cool the reacted agglomerates discharged from the second reactor segment to allow for handling and/or transport. The cooling facility may comprise a grate cooler. The grate cooler may be a rotating grate cooler. The rotating grate cooler may comprise spikes.

[0057] The system may include a crusher configured to crush the reacted agglomerates to form a powder product. The crushed may be the rotating grate cooler comprising spikes.

[0058] The system may include a preheater configured to preheat the particulate feed material prior to the reactor segment receiving the particulate feed material.

[0059] The singular forms “a”, “an” and “the” include plural referents unless the context clearly dictates otherwise.

[0060] Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

[0061] It will be appreciated embodiments may comprise steps, features and/or integers disclosed herein or indicated in the specification of this application individually or collectively, and any and all combinations of two or more of said steps or features.

Brief Description of Drawings

[0062] Embodiments will now be described by way of example only with reference to the accompany drawings in which:

[0063] Figure 1 is a schematic process flow diagram of system for the thermal treatment of a particulate material;

[0064] Figure 2 is a schematic cross-sectional side view of a vertical shaft reactor of the system of Figure 1; and

[0065] Figure 3 is a block flow diagram of a process for the thermal treatment of a particulate material, which may be executed by the system shown in the previous figures.

Description of Embodiments

[0066] In the drawings, reference numeral 100 generally designates a system for the thermal treatment of a particulate material. The system 100 is shown to include a first reactor segment 12 (Fig. 2) configured to receive the particulate material at a top end 12.1 thereof in order that the particulate material flows under gravity through the first reactor segment 12, and a first heating system 14 (Fig. 2) adjacent to and disposed along a length of the first reactor segment 12 to heat the particulate material flowing through the first reactor segment 12 from outside the first reactor segment 12 so as to activate the particulate material. The system 100 is further shown to include a compactor 16 for receiving and compacting the hot activated particulate material from the first reactor segment 12 to form agglomerates.

[0067] The system 100 and associated process (Fig. 3) for the thermal treatment of a particulate feed material is further herein described with reference to an example embodiment wherein the particulate material is received as a product of an industrial or comminution process as one of limestone, dolomite, magnesite, an SCM mixture, or cement meal, typically as a fine powder having an average particle diameter less than about 40 μ m.

[0068] Referring to Fig. 1, the particulate material is conveyed, as indicated by arrow A, from a storage facility (not shown) to a fusion operation including a cylindrical mill 18, where the particulate material is homogenised and fused, typically at ambient temperature, to increase the mean particle size and achieve a desired particle size distribution, generally in a range of 150 μ m to 200 μ m to exclude particle sizes that are readily entrained in a gas flow while also excluding unwanted larger heavier particles as will become apparent from the description below. From the cylindrical mill 18, the particulate material is passed through a preheater 20 and then introduced into a first

reactor segment 12 of a vertical shaft reactor 10. The first reactor segment 12 is configured to receive the particulate material through an inlet, such as disposed at a top end 12.1 of the reactor 10, as indicated by arrow B and shown in Fig. 2. The first reactor segment 12 in this example embodiment is the Calix Flash Calciner technology developed and owned by Calix Pty Ltd.

[0069] The particulate material is introduced into the first reactor segment 12 at the top end 12.1 in order that the particulate feed material flows under gravity through the first reactor segment 12 to a bottom end 12.2. The particulate material has a residence time in the first reactor segment 12 of typically less than 60 seconds. It will be appreciated that this residence time can however be influenced, at least in part, by the length of the first reactor segment 12 and gas flow through the first reactor segment, as further described below, and can be extended or shortened by providing a longer or shorter first reactor segment 12 respectively, as may be required.

[0070] Shown in Fig. 2, the vertical shaft reactor 10 further comprises a heating system 22 for the first reactor segment 12 and configured as electrical heating elements, such as induction or resistive heating coils, adjacent to and disposed along a length of the first reactor segment 12. The heating system 22 heats the particulate material flowing through the first reactor segment 12 from outside the first reactor segment 12. The heating system 22 heats the particulate material to a temperature up to about 1050°C to cause calcination of the particulate material. Consequently, the particulate material is activated to form a hot calcined particulate material, and an off-gas as CO₂.

[0071] Due to the high effective surface area of the particulate material and its preheating, heating in the first reactor segment 12 can occur rapidly, allowing what is commonly referred to as 'flash calcination' of the particulate material. This is further facilitated by the fusion operation 18 upstream from the vertical shaft reactor 10, mitigating against agglomeration of the particulate material in the first reactor segment 12 and its entrainment in the formed off-gas. The system 100 is shown to include a separator 24, such as one or more cyclones and/or filters in fluid flow connection with an off-gas outlet 26 disposed at the top end 12.1 of the first reactor segment 12. In this

manner, any solid particles entrained in the off-gas can be separated out from the off-gas and reintroduced, indicated by arrow C, into the first reactor segment 12, such as at the top end 12.1, while the off-gas can be discharged, indicated by arrow D.

[0072] Using a heating system 22 in this manner further allows for the at least partial electrification of the system 100, and may enable the use of renewable energy in the process. Accordingly, the system 100 is shown to comprise a renewable power facility 200 for powering the electrical heating elements, indicated by arrow E in Fig. 1. It will be appreciated that the renewable power facility 200 can receive power from a renewable energy source or may itself comprise a renewable energy source 210. The renewable power facility 200 can further include a power storage arrangement 220 with the electrical heating elements capable of being powered from either the renewable energy source 210 directly or indirectly via the power storage arrangement 220. The power storage arrangement 220 preferably comprises vanadium redox flow battery cells as a desirable cell technology for the storage from a potentially fluctuating and intermittent renewable energy supply. Alternatively, or additionally, the electrical heating elements can be powered from an electrical grid and therewith act as a demand side mechanism for balancing the electrical grid.

[0073] It will be appreciated that the heating system 22 can also be a furnace segment in thermal connection with the first reactor segment 12, wherein heat is generated from a combustion reaction and transferred to the first reactor segment 12 via a wall of the first reactor segment 12. Enabling a selection of the heating system 22 in this manner allows taking into account, by example, the type of particulate materials being processed and the need for a low emissions process, as may be required.

[0074] Advantageously, by heating the particulate material as described above from outside the first reactor segment 12, contamination of the hot activated particulate material by direct contact with a heating medium can be avoided allowing for a highly pure hot activated particulate material. To the extent necessary, a gas, such as an inert gas, can also be introduced at F (Fig. 2) into the reactor segment 12 to maintain a positive gauge pressure in the first reactor segment 12, which may inhibit any

deleterious gasses from entering the first reactor segment 12 (by example oxygen from air). The flow under gravity of the particulate material in the first reactor segment 12 thereby means the net flow, accounting for gas flows within the first reactor segment 12. Furthermore, it will be appreciated that the flow of the particulate material in the first reactor segment 12 can be dilute on the basis that the activation of the particulate material does not require contact between the particles.

[0075] The hot activated particulate material is discharged, indicated by arrow G, from the vertical shaft reactor 10 at the bottom end 12.1 of the first reactor segment 12 via a solids outlet 28. In this embodiment, the material is received by a compactor 16, such as one or more heat-resistant roller presses 30, at a temperature of approximately 700°C-800°C. The heat-resistant roller press 30 compacts the hot activated particulate material at a force of approximately 100kN/cm² to form agglomerates (which may be referred to as ‘briquettes’ or ‘hot briquettes’), preferably generally cylindrical or ‘cigar’ shaped agglomerates having a diameter of approximately 2cm and a length of approximately 3-5cm. It will be appreciated that the force at which the agglomerates are compacted can vary, at least in part, based on the dimensions of the agglomerates and the force can be adjusted to achieve any desired compressive strength, abrasion resistance and/or porosity in the agglomerates. It is unexpectedly and surprisingly found that the resultant nano porosity achieved by the calcination of the particulate material to form the hot activated particulate material as well as its elevated temperature and relatively low Youngs modulus can allow for efficient deformation and densification of the activated particulate material at the noted force to form a dense agglomerate. It will be appreciated such densification can enhance diffusion kinetics to increase the propensity of the agglomerate to undergo a target reaction, such as sintering or clinkering at suitably elevated temperatures.

[0076] The agglomerates are then introduced into a vertical second reactor segment 32 as a vertical kiln to form a packed bed in the second reactor segment 32. A synthesis gas, H, and oxygen gas, M, are then separately injected into the second reactor segment 32 at an elevated temperature and passed through the packed bed of agglomerates in a counter-current fashion. The “cigar” shape and size of the

agglomerates can enhance efficient packing that to mitigate or avoid high pressure gas injection while also inhibiting deleterious channelling through the packed bed.

[0077] The synthesis gas and oxygen gas introduced separately into the second reactor segment 32 allows for an oxyfuel flameless combustion reaction within the second reactor segment 32 which acts to heat the packed bed of agglomerates to a range of 1300°C to 1700°C. Consequently, as the agglomerates move through the packed bed, rapid sintering or clinkering is induced and, along with the oxyfuel combustion, a second reactor segment 32 CO₂ flue gas. Consequently, a residence time of an agglomerate within the packed bed may be less than 10 minutes, preferably around 5 minutes, which is substantially less than the 35 minutes or more required for clinkering or sintering in conventional rotary kiln processes.

[0078] The reacted agglomerates are discharged at I (Fig. 1) from a solids outlet of the second reactor segment 32 while the second reactor segment 32 CO₂ flue gas is separately discharged at J from a flue gas outlet of the second reactor segment 32. It will be appreciated that the second reactor segment 32 can include a discharge system configured to control the rate at which the reacted agglomerates are discharged from the second reactor segment 32, thereby control the rate at which the agglomerates move through the packed bed.

[0079] As the off-gas from the first reactor segment 12 and the second reactor segment 32 flue gas both comprise CO₂, the system 100 is shown to include a carbon capture facility 300 including cooling and gas cleaning 310 and liquefaction 320. The captured and liquefied CO₂ may then, by example, be transported to a methanol production facility. As a result, the unavoidable CO₂ emissions from processes such as cement and lime production can easily be separated for use or storage. Furthermore, by allowing the separate discharge of the off-gas from calcination in the first reactor segment 12 and the second reactor segment 32 flue gas from sintering or clinkering, the process provides a two-source approach that recognises that the residual impurities in the respective gas product streams may be different and thereby allow for CO₂ applications with different purity demands and reduced gas cleaning expenditure.

[0080] The sustainability of the process may be further enhanced as the oxygen gas required for the combustion reaction in the second reactor segment 32 can be obtained from a methanol electrolyser of the methanol production facility supplied by CO₂ from the system 100.

[0081] Furthermore, the system 100 is shown to include a gasification facility 400 including a gasifier 410 and gas cleaning operation 420, wherein a biomass feed, indicated by arrow K, is gasified with an oxygen feed, indicated by arrow L, from the methanol electrolyser of the methanol production facility. This gasification product is accordingly cleaned in the gas cleaning operation 420 to form the synthesis gas to the second reactor segment 32.

[0082] Operating the gasifier 410 to process the biomass feed may produce CO₂. The CO₂ from the gasification process may be removed by a pre-combustion capture process or stage, such as involving a Sorbent Enhanced Water Gas Shift (SEWGS) process. The SEWGS process produces a hydrogen stream which may be used for the oxyfuel combustion. The SEWGS sorbent may contain activated lime or dolime, such as made during the activation process of the first reactor segment 10.

[0083] Finally, the reacted agglomerates formed in the second reactor segment 32 are discharged from the second reactor segment 32 and cooled at a cooling facility 34 near the second reactor segment 32. In many industries it may be preferable to have the reacted agglomerates as a powder product, and accordingly the cooling facility 34 can comprise a rotating grate cooler with spikes such that the rotating grate cooler is not only configured to cool the reacted agglomerates discharged from the second reactor segment 32 but also to crush the reacted agglomerates to produce such a powder product for handling and/or transport at N.

[0084] It will be appreciated that, if necessary, the temperature in the second reactor segment 32 can be controlled by injecting CO₂ gas from the carbon capture facility 300 into the second reactor segment 32.

[0085] It will further be appreciated that the system 100 and associated process described above allows for various means of recycling heat throughout the process. By example, the waste heat obtained from cooling the solid product at the cooling facility 34 can be recycled along path O (Fig. 1) and used in the preheater 20 to preheat the particulate material.

[0086] In addition to possible equipment sizing considerations, the system 100 and associated process described above allows for scaling up to increase its capacity, by example through the use of a plurality of first reactor segments 10, second reactor segments 32 and/or compactors 16 arranged in various configurations. By non-limiting example, the system 100 can include the means of distributing the fused and preheated particulate material from a single fusion and preheater facility 500 to a plurality of first reactor segments 12, each first reactor segment 12 discharging the hot activated particulate material to a common compactor 16 to form agglomerates which are introduced into a common second reactor segment 32 and from which the reacted agglomerates are discharged to a common cooling facility 34. Furthermore, it is envisaged that the first reactor segment 10 and the second reactor segment 32 need not be distinct reactors and can be in the form of a unitary reactor 600 and/or in fluid flow communication via the compactor 16.

[0087] The system 100 and associated process as exemplified above is not only compatible with electricity and alternative fuels, but also provides viable, flexible and/or economical pathways to sustainable processing of various particulate materials.

[0088] It will be apparent to those persons skilled in the art that numerous variations and/or modifications may be made to the above-described embodiments, without departing from the broad general scope of the present disclosure. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive. As such, the present disclosure extends to all functionally equivalent processing equipment, structures, methods and uses that are within its scope. It will further be appreciated that the process of the present disclosure can be performed in a continuous, semi-continuous or batch fashion and thereby the steps of the process

provided for need not necessarily be executed sequentially or in the order described herein.

CLAIMS:

1. A process for the thermal treatment of a particulate material, the process including:
 - introducing the particulate material into a vertical first reactor segment, the particulate material introduced into the first reactor segment at a top end in order that the particulate material flows under gravity through the first reactor segment;
 - heating the particulate material from outside the first reactor segment to activate the particulate material; and
 - compacting the hot activated particulate material to form agglomerates.
2. The process of claim 1, wherein, prior to the compacting of the hot activated particulate material, additional particulate materials are added to the hot activated particulate material.
3. The process of claim 1 or 2, further including:
 - introducing the formed agglomerates into a top end of a vertical second reactor segment to form a packed bed in the second reactor segment;
 - heating the agglomerates in the packed bed to induce a target reaction within the agglomerates as the agglomerates move through the packed bed; and
 - discharging the reacted agglomerates from a bottom end of the second reactor segment.
4. The process of claim 3, wherein the reacted agglomerates are a densified product or a porous product.
5. The process of any one of the preceding claims, wherein an off-gas is discharged from the first reactor segment from an outlet disposed at a top end of the first reactor segment.

6. The process of claim 5, the process including passing the off-gas through a separator to at least partially separate out entrained solid particles in the off-gas to produce a cleaned off-gas.
7. The process of claim 6, including reintroducing the separated solid particles into the first reactor segment at the top end.
8. The process of any one of the preceding claims, wherein heating the particulate material from outside the first reactor segment is by means of a first heating system adjacent to and disposed along a length of the first reactor segment.
9. The process of claim 8, wherein the first heating system comprises electric heating elements.
10. The process of claim 9, wherein the electric heating elements are powered by a renewable energy source.
11. The process of claim 9, wherein the electric heating elements are powered by an electrical grid.
12. The process of claim 11, wherein the first heating system is used as a demand side mechanism for balancing the electrical grid.
13. The process of claim 8, wherein the first heating system is a furnace segment in thermal connection with the first reactor segment, wherein heat is generated from a combustion reaction.
14. The process of claim 13, wherein the combustion reaction in the furnace segment in thermal connection with the first reactor segment is oxyfuel combustion using a synthesis gas or gases and a source of oxygen to form a gas product as a furnace segment flue gas.

15. The process of claim 3, wherein heating the agglomerates in the packed bed in the second reactor segment comprises one or more of: heating from outside the second reactor segment; by means of a combustion reaction within the second reactor segment; by means of injecting a hot gas into the second reactor segment and passing the hot gas through the packed bed of agglomerates; and electric smelting.

16. The process of claim 15, wherein heating the agglomerates in the packed bed in the second reactor segment from outside the second reactor segment is by means of a second heating system adjacent to and disposed along a length of the second reactor segment.

17. The process of claim 16, wherein the second heating system comprises electric heating elements.

18. The process of claim 17, wherein the electric heating elements are powered by a renewable energy source.

19. The process of claim 17, wherein the electric heating elements are powered by an electrical grid.

20. The process of any one of claims 16 to 19, wherein the second heating system comprises an electric smelting furnace.

21. The process of claim 19, wherein the first heating system is used as a demand side mechanism for balancing the electrical grid.

22. The process of claim 16, wherein the second heating system is a furnace segment in thermal connection with the second reactor segment, wherein heat is generated from a combustion reaction.

23. The process of claim 22, wherein the combustion reaction in the furnace segment in thermal connection with the second reactor segment involves oxyfuel

combustion using a synthesis gas or gases and a source of oxygen to form a gas product as a furnace segment flue gas.

24. The process of claim 15, wherein heating the agglomerates in the packed bed is by means of a combustion reaction within the second reactor segment, the combustion reaction in the second reactor segment achieved by introducing a feed gas into the second reactor segment, the feed gas comprising one or any combination of a synthesis gas or gases; a source of oxygen; and a source of hydrogen.

25. The process of claim 24, wherein the feed gas comprises a combination of a synthesis gas or gases and a source of oxygen, the synthesis gas or gases and source of oxygen introduced separately into the second reactor segment so that on mixing, oxyfuel combustion heats the packed bed of agglomerates and forms a gas product as a second reactor segment flue gas.

26. The process of any one of claims 5 to 7, wherein the off-gas from the first furnace segment comprises CO₂, and further including capturing the CO₂ in a carbon capture facility.

27. The process of any claim 14 or 22, wherein the furnace segment flue gas comprises CO₂, and further including capturing the CO₂ in a carbon capture facility.

28. The process of claim 25, wherein the second reactor segment flue gas comprises CO₂, and further including capturing the CO₂ in a carbon capture facility.

29. The process of any one of claims 14, 22 and 25, wherein the synthesis gas or gases is formed from gasification of a biomass.

30. The process of claim 29, wherein the gasification of a biomass produces CO₂, and further including capturing the CO₂ in a carbon capture facility.

31. The process of claim 30, wherein the CO₂ may be captured by a pre-combustion capture process.

32. The process of claim 31, wherein the pre-combustion process is a Sorbent Enhanced Water Gas Shift (SEWGS) process.
33. The process of any one of claims 26 to 32, wherein the captured CO₂ from the carbon capture facility is used in a methanol, substitute aviation gas and/or hydrocarbon materials production facility.
34. The process of any one of the preceding claims, the process including homogenising the particulate material and/or fusing the particulate material to produce a particle size distribution in a range of 150µm to 350µm prior to introducing the particulate material into the first reactor segment.
35. The process of any one of the preceding claims, the process including preheating the particulate material prior to introducing the particulate material into the first reactor segment.
36. The process of any one of the preceding claims, wherein compacting the hot activated particulate material to form the agglomerates is at a linear pressure of up to 200kN/cm².
37. The process of claim 33, wherein the linear pressure is approximately 100 kN/cm².
38. The process of claim 3, wherein the first reactor segment and/or second reactor segment is operated at a positive gauge pressure.
39. The process of claim 3, the process including cooling and/or crushing the reacted agglomerates discharged from the second reactor segment to allow for handling and/or transport.
40. A system for the thermal treatment of a particulate material, the system including:

a vertical first reactor segment configured to receive the particulate material at a top end thereof in order that the particulate material flows under gravity through the first reactor segment and a first heating system adjacent to and disposed along a length of the first reactor segment to heat the particulate material flowing through the reactor segment from outside the reactor segment so as to activate the particulate material; and

a compactor for receiving and compacting the hot activated particulate material from the first reactor segment to form agglomerates.

41. The system of claim 40, further include an injection mechanism arranged to inject additional particulate materials to the hot activated particulate material prior to compaction by the compactor.

42. The system of claim 40 or 41, wherein the system includes a vertical second reactor segment configured to:

receive the agglomerates from the compactor at a top end thereof, the agglomerates forming a packed bed within the second reactor segment; and

heat the agglomerates in the packed bed to induce a target reaction within the agglomerates as the agglomerates move through the packed bed.

43. The system of claim 42, wherein the reacted agglomerates are discharged from an outlet of the second reactor segment disposed at a bottom end thereof.

44. The system of claim 43, wherein the second reactor segment includes a discharge system configured to control the rate of movement of the agglomerates through the packed bed in the second reactor segment.

45. The system of any one of claims 40 to 44, wherein the second reactor segment is configured to heat the agglomerates in the packed bed from outside the second reactor segment by one or more of: operating a second heating system arranged adjacent to and disposed along a length of the second reactor segment; causing a combustion reaction within the second reactor segment; injecting a hot gas into the

second reactor segment and passing the hot gas through the packed bed of agglomerates; and electrically smelting the agglomerates.

46. The system of any one of claims 40 to 45, wherein the first heating system comprises one or more electrical heating elements.

47. The system of any one of claims 42 to 46, wherein the second reactor segment is configured to heat the agglomerates in the packed bed from outside the second reactor segment by means of a second heating system adjacent to and disposed along a length of the second reactor segment.

48. The system of claim 47, the second heating system comprising one or more electrical heating elements.

49. The system of claim 46 or 48, wherein the system includes a renewable power facility for powering the one or more electrical heating elements.

50. The system of any one of claims 40 to 45, wherein the first heating system comprises a furnace segment in thermal connection with the first reactor segment, wherein heat is generated from a combustion reaction.

51. The system of claim 47, wherein the second heating system comprises a furnace segment in thermal connection with the second reactor segment, wherein heat is generated from a combustion reaction.

52. The system of any one of claims 47 to 49, wherein the second heating system comprises an electric smelting furnace.

53. The system of claim 50 or 51, wherein the combustion reaction in the furnace segment is oxyfuel combustion using a synthesis gas or gases and a source of oxygen, the combustion reaction forming a gas product as a furnace segment flue gas.

54. The system of claim 53, wherein the second reactor segment is configured to heat the agglomerates in the packed bed by means of a combustion reaction within the second reactor segment, the combustion reaction in the second reactor segment achieved by introducing a feed gas into the second reactor segment, the feed gas comprising one or any combination of a synthesis gas or gases; a source of oxygen; and a source of hydrogen.

55. The system of claim 54, wherein the target reaction and/or the combustion reaction within the second reactor segment produce a gas as a second reactor segment flue gas.

56. The system of any one of the preceding claims, wherein the first reactor segment is configured to discharge an off-gas from an outlet disposed at a top end of the first reactor segment.

57. The system of claim 56, wherein the include a separator in fluid flow connection the outlet disposed at the top end of the first reactor segment so as to receive the off-gas and at least partially separate out entrained solid particles.

58. The system of claim 57, wherein the separator is configured to reintroduce the separated solid particles into the first reactor segment at the top end thereof.

59. The system of claim 53, wherein the furnace segment flue gas comprises CO₂.

60. The system of claim 55, wherein the second reactor segment flue gas comprises CO₂.

61. The system of any one of claims 56 to 58, wherein the off-gas comprises CO₂.

62. The system of claim 49 or 50, wherein the system includes a gasification facility configured to produce the synthesis gas or gases from a biomass.

63. The system of claim 62, wherein operating the gasification facility produces CO₂.
64. The system of claim 63, wherein the gasification facility includes a pre-combustion capture stage to capture the CO₂.
65. The system of claim 64, wherein the pre-combustion stage is configured as a Sorbent Enhanced Water Gas Shift (SEWGS) process.
66. The system of any claim 59 or 61, wherein the system includes a carbon capture facility for capturing the CO₂.
67. The system of claim 64 or 66, wherein the captured CO₂ from the carbon capture facility is used in a methanol, substitute aviation gas and/or hydrocarbon materials production facility.
68. The system of any one claims 40 to 67, wherein the system includes a preheater for preheating the particulate material prior to being received by the first reactor segment.
69. The system of any one of claims 40 to 68, wherein the system includes a fusion and/or homogenising facility for fusing the particulate material to produce a particle size distribution in the range of 150µm to 350µm and/or homogenising the particulate material prior to introducing the particulate material into the first reactor segment.
70. The system of claim 69, wherein the fusion and/or homogenising facility comprises a cylindrical mill.
71. The system of claim 43, wherein the system includes a cooling facility configured to cool the reacted agglomerates discharged from the second reactor segment to allow for handling and/or transport.
72. The system of claim 71, wherein the cooling facility comprises a grate cooler.

73. The system of claim 72, wherein the grate cooler is a rotating grate cooler.
74. The system of any one of claims 71 to 73, wherein the system includes a crusher configured to crush the reacted agglomerates to form a powder product.
75. The system of claim 73, wherein the rotating grate cooler comprises spikes, the reacted agglomerates crushed to form a powder product by the rotating grate cooler.
76. The system of claim 40, wherein the first reactor segment and the second reactor segment are segments of a unitary reactor.
77. The system of any one of claims 40 to 76, wherein the second reactor segment is in fluid flow connection with the first reactor segment.