Fluidised bed reactors comprising heat carrying particles are used for processing a variety of feedstocks. They can be operated in a number of different fluidisation regimens. The preferred regime is selected depending on the feedstock in question and the desired chemistry to be obtained, which gives rise to a large number of different reactor configurations for fluidised bed reactors.

For conversion of biomass into bio-oil by pyrolysis, several reactor configurations have been investigated, such as dense phase (i.e. bubbling fluidised bed) and dilute phase (i.e. riser) reactors, as well as radically different reactor types, such as ablative pyrolysis reactors.

Examples of prior art disclosing the use of fluidised bed reactors include US 5,397,582 (Underwood), US 7,094,932 (Majerski), WO 2014/131764, WO 2012/115754, US 5,302,280 (Lomas), and WO 2017/216311 (Larsen et al.).

There remains a need for improved methods and systems for thermolytic fragmentation of a sugar into C1-C3 oxygenates, in particular which are suitable for industrial scale production.

Summary

According to an aspect of the present disclosure, there is provided a process for thermolytic fragmentation of a sugar into C1-C3 oxygenates, the process comprising the steps of:
a) providing an aqueous feedstock solution comprising the sugar;
b) providing a fluidised bed fragmentation reactor for thermolytically fragmenting the sugar and comprising fluidisable heat carrying particles;
c) introducing the feedstock solution into the reactor to thermolytically fragment the sugar to provide a fragmentation product comprising the C1-C3 oxygenates, wherein the temperature of the fragmentation product at an outlet of the reactor is at least 400°C;
d) cooling the fragmentation product downstream of the reactor to a cooling temperature of from 230°C to 390°C; and
e) separating solids from the fragmentation product cooled to the cooling temperature, wherein the solids comprise solids selected from fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

The present inventors have surprisingly discovered that by cooling the fragmentation product downstream of the reactor to the cooling temperature, the process provides for improvements

in efficiency and design, whilst achieving a good product yield of C1-C3 oxygenates. In particular, by virtue of the downstream cooling step, e.g. rather than including a cooling step within the reactor, the physical unit operation of the cooling step and the reactor can be arranged in different locations from each other. In this way, the reactor can be designed without the need to accommodate the physical unit operation of the cooling step, which reduces design complexity and installation complexity, and improves space-efficiency and ease of handling. With regard to reducing installation complexity, the physical unit operation of the cooling step can be located closer to ground level than the reactor and installed independently of the reactor. With regard to space-efficiency and ease of handling, as the reactor can be designed without the need to accommodate the physical unit operation of the cooling step, the reactor can be more compact and of a lower mass. Moreover, for example, the physical unit operation of the cooling step can be connected to the reactor (e.g. in a modular fashion) once the reactor has been installed. The cooling to the cooling temperature downstream of the reactor unexpectedly led to these advantages as well as a good product yield of C1-C3 oxygenates.

The afore-mentioned advantages are particularly beneficial in the context of industrial production plants, where significant capital expenditure (CAPEX) and operational expenditure (OPEX) can be used for building and maintaining process equipment and in which product yield is a primary consideration.

In the present context, the terms “downstream” and “upstream” are with respect to the direction in which the components flow. For example, the outlet of the reactor is downstream of the point at which the feedstock solution is introduced into the reactor, given that components flow from the point at which the feedstock solution is introduced to the outlet of the reactor.

a) the feedstock solution

The process comprises providing an aqueous feedstock solution comprising the sugar.

In one example, the total sugar content in the feedstock solution is at least 30 wt.%, such as at least 35 wt.%, at least 40 wt.%, at least 45 wt.%, at least 50 wt.%, at least 55 wt.%, at least 60 wt.%, at least 65 wt.%, at least 70 wt.%, at least 75 wt.%, at least 80 wt.%, at least 85 wt.%, at least 90 wt.%, or at least 95 wt.%, based on the total weight of the feedstock solution.

In one example, the total sugar content in the feedstock solution is no greater than 99.9 wt.%, such as no greater than 99.5 wt.%, no greater than 99 wt.%, no greater than 95 wt.%, no greater than 85 wt.%, or no greater than 80 wt.%, based on the total weight of the feedstock solution.

In one example, the total sugar content in the feedstock solution is from 30 to 99 wt.%, such as from 40 to 90 wt.%, or from 50 to 80 wt.%, based on the total weight of the feedstock solution.

In one example, the feedstock solution is a liquid.

In one example, the water content in the feedstock solution is at least 20 wt.%, such as at least 25 wt.%, at least 30 wt.%, at least 35 wt.%, at least 40 wt.%, at least 45 wt.%, at least 50 wt.%, based on the total weight of the feedstock solution.

In one example, the water content in the feedstock solution is no greater than 70 wt.%, such as no greater than 65 wt.%, no greater than 60 wt.%, no greater than 55 wt.%, no greater than 50 wt.%, or no greater than 45 wt.%, based on the total weight of the feedstock solution.

In one example, the total sugar content in the aqueous feedstock solution is from 20 to 70 wt.%, such as from 25 to 60 wt.%, or from 30 to 50 wt.%, based on the total weight of the feedstock solution.

In one example, the sugar is a carbohydrate comprising one or more C6 saccharide units and/or C5 saccharide units.

In one example, the sugar is a monosaccharide or a disaccharide.

In one example, the sugar is selected from sucrose, lactose, xylose, arabinose, ribose, mannose, tagatose, galactose, glucose and fructose.

In one example, the feedstock solution may comprise a sugar syrup.

In one example, the feedstock solution comprises more than one sugar.

Each sugar may be independently as described herein.

b) providing a fluidised bed fragmentation reactor for thermolytically fragmenting the sugar and comprising fluidisable heat carrying particles

The process comprises providing a fluidised bed fragmentation reactor for thermolytically fragmenting the sugar and comprising fluidisable heat carrying particles.

As will be understood by those skilled in the art, a fluidised bed reactor is a reactor which accommodates a bed of particles which may be fluidised, e.g. by a fluidisation gas which may be introduced at the base of the reactor. The velocity and physical properties of the fluidisation gas combined with the physical properties of the fluidisable particles may regulate the fluidisation state of the fluidisable particles within the bed. A dense bed/turbulent bed/bubbling bed has a superficial velocity of the fluidisation gas within the reactor of from 0.01 to 2 m/s. A fast bed (also termed a riser/transport reactor) may have a superficial velocity of fluidisation gas within the reactor of from 3 to 22 m/s. The exact velocity range is, however, dependent on the physical properties of the fluidisable particles and the fluidisation gas, and can be determined experimentally or calculated by those skilled in the art.

In one example, the fluidised bed fragmentation reactor is operative in the bubbling fluidisation regime, the slugging fluidisation regime, the turbulent fluidisation regime, the fast fluidisation regime, and/or the pneumatic conveying regime.

In one example, the fluidised bed fragmentation reactor is operative in the fast fluidisation regime. Such a reactor is also termed a “riser type reactor”. Thus, in one example, the reactor is a riser type reactor.

In one example, the reactor comprises a riser.

In one example, the riser extends vertically.

In one example, the riser (e.g. a lower part of the riser) comprises a fluidisation gas inlet.

In one example, the riser (e.g. a lower part of the riser) comprises a fluidisable particle inlet.

In one example, the riser (e.g. a lower part of the riser) comprises a feedstock inlet.

In one example, the fluidisable particle inlet is provided downstream of the fluidisation gas inlet.

In one example, the feedstock solution inlet is provided downstream of the fluidisable particle inlet.

In one example, the fluidisable heat carrying particles form a dense phase fluidised bed in a zone between the fluidisable particle inlet and the feedstock solution inlet.

In one example, the riser (e.g. a lower part of the riser) comprises a fluidisable particle and fluidisation gas inlet. In this way, the fluidisable heat carrying particles and the fluidisation gas can be introduced into the reactor via a common inlet, e.g. sequentially or at the same time.

In one example, the feedstock solution inlet is provided downstream of the fluidisable particle and fluidisation gas inlet.

In one example, the method comprises introducing fluidisable heat carrying particles into the reactor.

In one example, the method comprises introducing fluidisable heat carrying particles into the reactor via the fluidisable particle inlet.

In one example, the method comprises introducing fluidisable heat carrying particles into the reactor via the fluidisable particle and fluidisation gas inlet.

In one example, the temperature of the fluidisable heat carrying particles within the reactor is at least 400°C, such as at least 450°C, at least 500°C, at least 550°C, at least 600°C, or at least 650°C.

In one example, the temperature of the fluidisable heat carrying particles within the reactor is no greater than 800°C, such as no greater than 700°C, or no greater than 650°C.

In one example, the temperature of the fluidisable heat carrying particles within the reactor is from 400 to 800°C, such as from 500 to 800°C, from 450 to 650°C, or from 550 to 650°C.

In one example, the temperature of the fluidisable heat carrying particles at the fluidisable particle inlet (or the fluidisable particle and fluidisation gas inlet) is at least 400°C, such as at least 450°C, at least 500°C, at least 550°C, at least 600°C, or at least 650°C.

In one example, the temperature of the fluidisable heat carrying particles at the fluidisable particle inlet (or the fluidisable particle and fluidisation gas inlet) is no greater than 800°C, such as no greater than 700°C, or no greater than 650°C.

In one example, the temperature of the fluidisable heat carrying particles at the fluidisable particle inlet (or the fluidisable particle and fluidisation gas inlet) is from 400 to 800°C, such as from 500 to 800°C, from 450 to 650°C, or from 550 to 650°C.

In one example, the pressure at the outlet of the reactor is at least 0.9 bara, such as at least 1 bara, at least 1.2 bara, at least 1.4 bara, at least 1.6 bara, at least 1.7 bara, at least 1.8 bara, at least 2 bara, or at least 2.2 bara.

In one example, the pressure at the outlet of the reactor is no greater than 8 bara, such as no greater than 6 bara, no greater than 5 bara, no greater than 4 bara, no greater than 3.5 bara, no greater than 3 bara, no greater than 2.9 bara, or no greater than 2.8 bara.

In one example, the pressure at the outlet of the reactor is from 0.9 to 8 bara, such as from 1 to 6 bara, from 1.1 to 5 bara, from 1.2 to 4 bara, from 1.5 to 3 bara, from 1.6 to 2.9 bara, from 1.7 to 2.8 bara, from 1.8 to 2.8 bara, from 2 to 2.8 bara, or from 2.2 to 2.8 bara.

In one example, the fluidisable heat carrying particles are selected from sand, mullite, silica, glass, alumina, silica-alumina, steel, and silicon carbide.

In one example, the mean particle size of the fluidisable heat carrying particles is from 20 to 400 μm, such as from 20 to 300 μm, or from 20 to 200 μm. The particle size distribution can be measured by laser diffraction spectroscopy, microscopy, electrical zone sensing. The mean particle size can be subsequently calculated from the particle size distribution. The mean particle size may be the Sauter mean particle size. Those skilled in the art will appreciate that other mean particles sizes are envisaged.

As will be appreciated by those skilled in the art, the flow of the fluidisable heat carrying particles within the reactor may be adjusted relative to the flow of the feedstock solution so

as to provide the desired amount of heat to the feedstock solution. Fluidisable particles with a high heat capacity may require a lower mass flow rate than fluidisable particles with a lower heat capacity.

c) introducing the feedstock solution into the reactor to thermolytically fragment the sugar to provide a fragmentation product comprising the C1-C3 oxygenates, wherein the temperature of the fragmentation product at an outlet of the reactor is at least 400°C

The method comprises introducing the feedstock solution into the reactor to thermolytically fragment the sugar to provide a fragmentation product comprising the C1-C3 oxygenates, wherein the temperature of the fragmentation product at an outlet of the reactor is at least 400°C.

The thermolytic fragmentation of sugar is an endothermic reaction, mainly due to evaporation of any liquid in the feedstock solution and the reaction enthalpy of thermolytic fragmentation of the sugar to the oxygenates.

In one example, the temperature of the fragmentation product at an outlet of the reactor is at least 420°C, such as at least 430°C, at least 440°C, at least 450°C, at least 460°C, or at least 470°C.

In one example, the temperature of the fragmentation product at an outlet of the reactor is no greater than 550°C, such as no greater than 530°C, no greater than 520°C, no greater than 510°C, no greater than 500°C, or no greater than 490°C.

In one example, the temperature of the fragmentation product at an outlet of the reactor is from 400 to 600°C, such as from 420 to 550°C, from 450 to 510°C, from 460 to 500°C, or from 470 to 490°C.

In one example, in step c) the feedstock solution is introduced into the reactor at a rate of at least 1000 kg/h (kilogrammes per hour). In one example, in step c) the feedstock solution is introduced into the reactor at a rate of at least 2000 kg/h. In one example, in step c) the feedstock solution is introduced into the reactor at a rate of at least 5000 kg/h. In one example, in step c) the feedstock solution is introduced into the reactor at a rate of at least 10000 kg/h. In one example, in step c) the feedstock solution is introduced into the reactor at a rate of at

least 15000 kg/h. In one example, in step c) the feedstock solution is introduced into the reactor at a rate of at least 20000 kg/h.

There may be no upper limit as to the rate at which feedstock solution is introduced into the reactor in step c). In one example, in step c) the feedstock solution is introduced into the reactor at a rate of no greater than 1000000 kg/h. In one example, in step c) the feedstock solution is introduced into the reactor at a rate of no greater than 100000 kg/h.

Fluidisation gas

In one example, the process comprises introducing a fluidisation gas into the reactor.

As will be understood by those skilled in the art, the fluidisation gas fluidises the fluidisable heat carrying particles in the reactor.

In one example, the process comprises introducing a fluidisation gas into the reactor via the fluidisation gas inlet.

In one example, the process comprises introducing a fluidisation gas into the reactor via the fluidisable particle and fluidisation gas inlet.

When the feedstock solution encounters the fluidisable heat carrying particles in the reactor, a vaporisation zone is formed in which the liquid evaporates and gaseous products are generated via sugar fragmentation. This results in an increase in the superficial velocity of the gas products thereby entraining the fluidisable heat carrying particles. Accordingly, downstream of the feedstock solution inlet, the fluidisable heat carrying particles and the feedstock solution form a fast bed above the vaporisation zone.

In one example, step c) comprises introducing the feedstock solution and the fluidisation gas into the reactor to thermolytically fragment the sugar to provide the fragmentation product.

In one example, in step c) the feedstock solution is entrained in the fluidisation gas.

In one example, the fluidisation gas comprises water (e.g. steam).

In one example, the fluidisation gas consists essentially of water (e.g. steam).

In one example, the fluidisation gas consists of water (e.g. steam).

Herein, “water” and “steam” may be used interchangeably.

In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of at least 100 kg/h. In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of at least 500 kg/h. In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of at least 1000 kg/h. In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of at least 2000 kg/h. In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of at least 4000 kg/h. In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of at least 5000 kg/h.

There may be no upper limit as to the rate at which the fluidisation gas is introduced into the reactor in step c). In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of no greater than 50000 kg/h. In one example, in step c) the fluidisation gas is introduced into the reactor at a rate of no greater than 20000 kg/h.

Atomisation gas

In one example, the process comprises introducing an atomisation gas into the reactor.

As will be understood by those skilled in the art, the atomisation gas is used to atomise the feedstock solution introduced into the reactor. The term atomising is meant to refer to turning a liquid into small droplets.

In one example, the atomisation gas and the feedstock solution are introduced into the reactor such that the feedstock solution is atomised by the atomisation gas.

In one example, the atomisation gas comprises water (e.g. steam).

In one example, the atomisation gas consists essentially of water (e.g. steam).

In one example, the atomisation gas consists of water (e.g. steam).

In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 50 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 100 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 200 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 500 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 800 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 1000 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of at least 1200 kg/h.

There may be no upper limit as to the rate at which the atomisation gas is introduced into the reactor in step c). In one example, in step c) the atomisation gas is introduced into the reactor at a rate of no greater than 20000 kg/h. In one example, in step c) the atomisation gas is introduced into the reactor at a rate of no greater than 10000 kg/h.

Water introduced

The process comprises introducing water into the reactor.

The water may be introduced in the form of one or both of gas (steam) and liquid. The water may be introduced in various different ways, and by one or more different means, including, for example, via the feedstock solution and/or via the fluidisation gas and/or via the atomisation gas).

In one example, water is introduced into the reactor via the atomisation gas.

In one example, water is introduced into the reactor via the feedstock solution.

The fragmentation product

The fragmentation product comprises C1-C3 oxygenates resulting from the thermolytic fragmentation of the feedstock solution. The fragmentation product provided in step (c) is a crude product. The fragmentation product provided in step (c) comprises the solids.

In one example, in step c) the fragmentation product is a solids-dense fragmentation product.

In one example, the solids-dense fragmentation product comprises the C1-C3 oxygenates and the solids.

In one example, step e) comprises separating solids from the solids-dense fragmentation product cooled to the cooling temperature to provide a solids-lean fragmentation product, wherein the solids comprise solids selected from the fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, the solids-lean fragmentation product comprises the C1-C3 oxygenates.

In one example, the solids-lean fragmentation product comprises a lower amount of the solids than the solids-dense fragmentation product.

The terms “lean” in “solids-lean” and “dense” in “solids-dense” are relative to each other.

In one example, the C1-C3 oxygenates comprise one, more, or each of formaldehyde (C1), glycolaldehyde (C2), glyoxal (C2), pyruvaldehyde (C3), and acetol (C3). For most uses, the C2 and the C3 oxygenates are most valuable.

In one example, the fragmentation product comprises a mixture of two or more of C1-C3 oxygenates. The mixture may be interchangeably referred to as a C1-C3 oxygenate mixture, a C1-C3 oxygenate product, or C1-C3 oxygenates.

In one example, the fragmentation product comprises glycolaldehyde.

In one example, the fragmentation product includes a major portion of glycolaldehyde.

In one example, the fragmentation product comprises glycolaldehyde in an amount of at least 10 wt.%, such as at least 20 wt.%, at least 30 wt.%, at least 40 wt.%, at least 50 wt.%, at least 60 wt.%, or at least 70 wt.%, based on the total weight of the fragmentation product.

In one example, the fragmentation product comprises one or more of glycolaldehyde or glyoxal in an amount of at least 10 wt.%, such as at least 20 wt.%, at least 30 wt.%, at least 40 wt.%, at least 50 wt.%, at least 60 wt. %, at least 70 wt. %, or at least 80 wt. %, based on the total weight of the fragmentation product.

In one example, the fragmentation product comprises one or more of pyruvaldehyde or acetol in an amount of at least 3 wt. %, such as at least 5 wt. %, or at least 7 wt. %, based on the total weight of the fragmentation product.

In one example, the total amount of C1-C3 oxygenates in the fragmentation product is no greater than 99 wt.%, such as no greater than 95 wt.%, or no greater than 90 wt.%, based on the total weight of the fragmentation product.

In one example, “based on the total weight of the fragmentation product” refers to the fragmentation product provided in step (c) (e.g. the solids-dense fragmentation product).

In one example, “based on the total weight of the fragmentation product” refers to the fragmentation product following step (e) (e.g. the solids-lean fragmentation product).

In one example, “based on the total weight of the fragmentation product” refers to the fragmentation product not including the solids.

d) cooling the fragmentation product downstream of the reactor to the cooling temperature

The process comprises cooling the fragmentation product downstream of the reactor to a cooling temperature of from 230°C to 390°C.

The “cooling temperature” corresponds to an average temperature of the fragmentation product after step d) of cooling.

In one example, the cooling temperature is from 250 to 390°C.

In one example, the cooling temperature is from 260 to 385°C.

In one example, the cooling temperature is from 270 to 380°C.

In one example, the cooling temperature is from 300 to 375°C.

In one example, the cooling temperature is from 330 to 370°C.

In one example, step d) comprises indirectly cooling the fragmentation product to the cooling temperature.

In one example, step d) comprises cooling the fragmentation product to the cooling temperature using a cooling device.

In one example, the cooling device is a heat exchanger.

In one example, the cooling device is an indirect heat exchanger.

In one example, step d) is the earliest step of cooling the fragmentation product.

In one example, no step of cooling the fragmentation product is performed within the reactor.

In one example, no step of cooling the fragmentation product is performed prior to step d).

In one example, step d) is performed at a location below the location at which the reactor is provided (with respect to sea level).

In one example, the cooling device (e.g. the heat exchanger) is provided at a location below the location at which the reactor is provided (with respect to sea level).

In one example, a lowermost surface of the cooling device (e.g. the heat exchanger) is provided at a location below the location at which a lowermost surface of the reactor is provided (with respect to sea level).

In one example, no cooling step is conducted within the reactor.

e) separating solids from the fragmentation product cooled to the cooling temperature, wherein the solids comprise solids selected from the fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof

The process comprises separating solids from the fragmentation product cooled to the cooling temperature, wherein the solids comprise solids selected from the fluidisable heat

carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, step e) comprises separating at least 50 wt.%, at least 60 wt.%, at least 70 wt.%, at least 80 wt.%, at least 90 wt.%, at least 95 wt.%, or at least 99 wt.% of the solids from the fragmentation product cooled to the cooling temperature, based on the total weight of the solids.

In one example, step e) comprises separating no greater than 99.999 wt.%, such as no greater than 99.99 wt.%, no greater than 99.9 wt.%, no greater than 99.5 wt.%, or no greater than 99 wt.% of the solids from the fragmentation product cooled to the cooling temperature, based on the total weight of the solids.

In one example, step e) comprises separating substantially all of the solids from the fragmentation product cooled to the cooling temperature.

In one example, step e) comprises separating the solids from the fragmentation product cooled to the cooling temperature using a physical separation device.

In one example, the physical separation device is a particle separator.

In one example, the physical separation device is a low volume separator.

In one example, the physical separation device is a change of direction separator.

In one example, the physical separation device is a cyclone.

In one example, the physical separation device is a filter.

In one example, the filter is selected from: a metal filter and a ceramic filter.

In one example, the filter comprises a filter element. The filter element can be considered as the material through which the fragmentation product comprising the solids (the filtration medium) is filtered, thereby to separate the solids from the fragmentation product.

In one example, the filter element comprises a filtration surface. The filtration surface can also be referred to as a filtration area. The filtration surface may be considered as an outer surface of the filter element. The filtration surface may be considered as the interface through which the fragmentation product comprising the solids enters the filter element in use. The filtration surface may be for separating the solids from the fragmentation product. In this way, the solids may collect on the filtration surface in use.

In one example, the filter element comprises a porous matrix.

In one example, the porous matrix is selected from; a porous fibrous matrix; a porous mesh matrix; a porous matrix comprising sintered spheres; a porous metal matrix (e.g. a sintered porous metal matrix); a porous ceramic matrix; and combinations thereof.

In one example, the porous matrix is a porous fibrous matrix. In one example, the porous fibrous matrix is a porous fibrous metal matrix. In one example, the porous fibrous matrix is a sintered porous fibrous metal matrix.

In one example, the filter comprises a plurality of the filter elements. Each of the filter elements may be independently as described herein.

In one example, the filter is a candle filter.

In one example, the filter is a bag filter.

In one example, the filter has an efficiency of at least 99.9% for particles having a size of at least 50 micrometres, such as at least 30 micrometres, at least 20 micrometres, or at least 10 micrometres.

In one example, multiple of the physical separation devices are employed. Each of the physical separation devices may be independently as described herein.

Residence time

In one example, the mean residence time of the fragmentation product between step d) and step e) is no greater than 50 s, such as no greater than 45 s, no greater than 40 s, no greater than 35 s, no greater than 30 s, no greater than 25 s, or no greater than 20 s.

In one example, the mean residence time of the fragmentation product between step d) and step e) is at least 0.1 s, such as at least 1 s, at least 3 s, at least 5 s, at least 8 s, at least 10 s, at least 12 s, or at least 15 s.

In one example, the mean residence time of the fragmentation product between step d) and step e) is from 0.1 to 50 s, such as from 1 to 40 s, or from 2 to 20 s.

"Between step d) and step e)" means between the end of step d) and the start of step e). Where a cooling device is used in step d), "between step d) and step e)" means between the exit of the fragmentation product from the cooling device and step e). Where a separation device is used in step e), "between step d) and step e)" means between step d) and entry of the fragmentation product into the separation device. Where a cooling device is used in step d) and a separation device is used in step e), "between step d) and step e)" means between the exit of the fragmentation product from the cooling device and entry of the fragmentation product into the separation device.

In one example, the mean residence time of the fragmentation product in step e) is from 5 to 50 s, such as from 8 to 30 s, from 10 to 25 s, from 14 to 22 s, from 15 to 20 s, 16 to 17 s.

"In step e)" means the duration of the separating process in step e). Where a physical separation device is used in step e), "in step e)" means from entry of the fragmentation product into the physical separation device to exit of the fragmentation product from the physical separation device. For example, where a filter is used in step e), "in step e)" means from entry of the fragmentation product into the filter to exit of the fragmentation product from the filter.

Superficial velocity

In one example, where a filter is used in step e), the superficial velocity of the fragmentation product at the filtration surface of the filter is from 0.1 to 3 cm/s, such as from 0.15 to 2.5 cm/s, from 0.2 to 2 cm/s, 0.25 to 1.5 cm/s, 0.3 to 1 cm/s, 0.3 to 0.75 cm/s, from 0.35 to 0.6 cm/s, or from 0.4 to 0.5 cm/s.

Those skilled in the art would know how to calculate the surface filtration velocity.

The solids

The solids comprise solids selected from the fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

As the fluidisable heat carrying particles are fluidised within the reactor, an amount of the particles can be transported out of the reactor, e.g. via an outlet of the reactor. The fragments of the particles can be formed by abrasion or breakage of the particles, e.g. by mechanical interaction between the particles themselves and/or between the particles and the reactor.

The by-products can be viscous and/or sticky. Without removal of the by-products, these can adhere to the filter (when present) and/or equipment downstream of the reactor. For example, when a filter is used, the by-products can form an increasingly large, sticky filter cake on the filter over time, such that, eventually, the filter cake needs to be removed.

In one example, the solids substantially comprise solids selected from the fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, the solids consist essentially of solids selected from the fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, the solids consist of solids selected from the fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, the process is suitable for processing amounts of sugar of greater than 1,000 tons per year per fragmentation reactor, such as greater than 5000 tons per year per fragmentation reactor, greater than 10000 tons per year per fragmentation reactor, greater than 50000 tons per year per fragmentation reactor, greater than 100000 tons per year per fragmentation reactor, or greater than 1000000 tons per year per fragmentation reactor, based on weight of dry sugar.

In one example, the process is suitable for processing amounts of sugar of no greater than 10000000 tons per year per fragmentation reactor, such as no greater than 5000000 tons per

year per fragmentation reactor, or no greater than 2000000 tons per year per fragmentation reactor, based on weight of dry sugar.

In one example, the thermolytic fragmentation process is operated as a continuous process.

Further process steps

In one example, the process comprises one or more further separation steps between step c) and step d), wherein the or each separation between step c) and step d) comprises separating solids from the fragmentation product, wherein the solids comprise solids selected from fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof. In one example, the or each separation between step c) and step d) is performed within the reactor.

In one example, the or each separation step between step c) and step d) comprises separating at least 50 wt.%, at least 60 wt.%, at least 70 wt.%, at least 80 wt.%, at least 90 wt.%, at least 95 wt.%, or at least 99 wt.% of the solids from the fragmentation product based on the total weight of the solids.

In one example, the or each separation step between step c) and step d) comprises separating no greater than 99.9 wt.%, such as no greater than 99.5 wt.%, no greater than 99 wt.%, no greater than 95 wt.%, no greater than 90 wt.%, or no greater than 80 wt.% of the solids from the fragmentation product based on the total weight of the solids.

In one example, the process comprises, between step c) and step d), a primary separation and/or a secondary separation. In one example, the primary separation and/or the secondary separation are performed within the reactor.

In one example, the primary separation comprises separating solids from the fragmentation product, wherein the solids comprise solids selected from fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, the primary separation comprises separating at least 50 wt.%, at least 60 wt.%, at least 70 wt.%, at least 80 wt.%, at least 90 wt.%, at least 95 wt.%, or at least 99 wt.% of the solids from the fragmentation product based on the total weight of the solids.

In one example, the primary separation comprises separating no greater than 99.9 wt.%, such as no greater than 99.5 wt.%, no greater than 99 wt.%, no greater than 95 wt.%, no greater than 90 wt.% or no greater than 80 wt.% of the solids from the fragmentation product based on the total weight of the solids.

In one example, the secondary separation comprises separating solids from the fragmentation product, wherein the solids comprise solids selected from fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, the secondary separation comprises separating at least 50 wt.%, at least 60 wt.%, at least 70 wt.%, at least 80 wt.%, at least 90 wt.%, at least 95 wt.%, or at least 99 wt.% of the solids from the fragmentation product based on the total weight of the solids.

In one example, the secondary separation comprises separating no greater than 99.9 wt.%, such as no greater than 99.5 wt.%, no greater than 99 wt.%, no greater than 95 wt.%, no greater than 90 wt.%, or no greater than 80 wt.% of the solids from the fragmentation product based on the total weight of the solids.

The one or more further separation steps between step c) and step d) may help to reduce the amount of the solids in the fragmentation product prior to step d). In this way, less energy is wasted in cooling the heat carrying particles in step d).

The process according to the present disclosure may provide a fragmentation product which is subjected to one or more further processing steps. For example, subsequent to step d), the fragmentation product may be further processed by one or more of chemical conversion (e.g. into another product, e.g. via a hydrogenation reactor), purification (e.g. to reduce the presence of any impurities), and separation (e.g. to provide specific oxygenates or a specific oxygenate mixture).

According to another aspect of the present disclosure, there is provided a system for thermolytic fragmentation of a sugar into C1-C3 oxygenates, the system comprising:

a) an aqueous feedstock solution comprising the sugar;

b) a fluidised bed fragmentation reactor configured to thermolytically fragment the sugar and comprising fluidisable heat carrying particles thereby to provide a fragmentation product comprising the C1-C3 oxygenates, wherein the temperature of the fragmentation product at an outlet of the reactor is at least 400°C;

c) means for cooling the fragmentation product downstream of the reactor to a cooling temperature of from 230°C to 390°C; and

d) a separation device configured to separate solids from the fragmentation product cooled to the cooling temperature, wherein the solids comprise solids selected from fluidisable heat carrying particles, fragments of the fluidisable heat carrying particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

According to another aspect of the present disclosure, there is provided a system for thermolytic fragmentation of a sugar into C1-C3 oxygenates, the system comprising:

a) a fluidised bed fragmentation reactor configured to thermolytically fragment the sugar thereby to provide a fragmentation product comprising the C1-C3 oxygenates; and

b) means for cooling the fragmentation product downstream of the reactor,

wherein the means for cooling the fragmentation product is provided at a location below the location at which the reactor is provided.

According to another example of the present disclosure, there is provided a system for thermolytic fragmentation of a sugar into C1-C3 oxygenates, the system comprising:

a) a fluidised bed fragmentation reactor configured to thermolytically fragment the sugar thereby to provide a fragmentation product comprising the C1-C3 oxygenates; and

b) means for cooling the fragmentation product downstream of the reactor to a cooling temperature,

wherein the means for cooling the fragmentation product is provided at a location below the location at which the reactor is provided (with respect to sea level).

In one example, the reactor and the means for cooling are in the form of separate physical structures.

According to another example of the present disclosure, there is provided a system for thermolytic fragmentation of a sugar into C1-C3 oxygenates, the system comprising:

a) a fluidised bed fragmentation reactor configured to thermolytically fragment the sugar thereby to provide a fragmentation product comprising the C1-C3 oxygenates; and

b) means for cooling the fragmentation product downstream of the reactor to a cooling temperature.

In one example, the means for cooling is a cooling device. The cooling device may be as defined herein.

Any example of the present disclosure may comprise any feature or features of any other example of the present disclosure. The features of any example of the present disclosure may be as

described herein in relation to any other example of the present disclosure. For example, the systems according to the present disclosure may be characterised by any of the features of the processes according to the present disclosure, and vice-versa.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are explained by way of examples and with reference to the accompanying drawings. The appended drawings illustrate only examples of embodiments of the present invention, and they are therefore not to be considered limiting of its scope, as the invention may admit to other alternative embodiments.

Fig. 1 shows a cross sectional side view of a fragmentation reactor which forms part of a system according to an embodiment of the invention;
Fig. 2 shows a top view of the fragmentation reactor of Fig. 1;
Fig. 3 shows a cross sectional side view of a reheater which forms part of a system according to an embodiment of the invention;
Fig. 4 shows a cross sectional side view of a system according to an embodiment of the invention (not all components of the system are shown), the system comprising a fragmentation reactor in fluid communication with a reheater;
Fig. 5 shows a block diagram of a system according to an embodiment of the invention (not all components of the system are shown);
Fig. 6 shows the temperature profiles of the fluidisable particle inlet, the outlet of the reactor, and the filter of an example;
Fig. 7 shows the carbon yield in glycolaldehyde carbon recovery, and in C1-C3 oxygenates (in total) carbon recovery, as a function of filtration temperature;
Fig. 8 is a schematic diagram of a candle filter; and
Fig. 9 shows a schematic drawing of a fragmentation reactor which forms part of a system according to an embodiment of the invention.

Position numbers

1. Fragmentation reactor
2. Fragmentation riser
3. First particle separator
4. Second particle separator
5. Cooling section