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 e.g. 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; and

d) separating solids from the 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;

wherein the temperature of the fragmentation product at an outlet of the reactor is at least 250°C, such as at least 300°C, at least 350°C, at least 400°C, or at least 450°C, and

wherein the water content is at least 40 vol.%, based on all gas phase constituents.

According to an example 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; and

d) separating solids from the 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;

wherein the temperature of the fragmentation product at an outlet of the reactor is at least 250°C, such as at least 300°C, at least 350°C, at least 400°C, or at least 450°C, and

wherein the partial pressure of steam is greater than 650 mbar.

The present inventors have investigated means for providing improved processes and systems for thermolytic fragmentation of a sugar into C1-C3 oxygenates. Such processes and systems typically employ a fluidised bed fragmentation reactor for thermolytically fragmenting a sugar to provide a fragmentation product comprising the C1-C3 oxygenates.

During such investigations, the present inventors observed problems in the operation of equipment downstream of the reactor. The present inventors surprisingly discovered the presence of material adhered to the equipment. In some instances, this material resulted in obstruction or blockage in the equipment.

Upon making such discoveries, the present inventors conducted experiments to characterise the material, and identified that such material comprised solids selected from fluidisable heat carrying particles (transported from the reactor), fragments of the fluidisable heat carrying particles (transported from the reactor), by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

The present inventors tested various means (e.g. a physical separation device such as a filter) for reducing the amount of the solids transported downstream of the reactor. Whilst such means initially helped to achieve this, the present inventors further discovered that

**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 particles into the reactor via the fluidisable particle inlet.

In one example, the method comprises introducing fluidisable 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 250°C, such as at least 300°C, at least 350°C, at least 400°C, 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 250°C, such as at least 300°C, at least 350°C, at least 400°C, 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 heat carrying particles with a high heat capacity may require a lower mass flow rate than fluidisable heat carrying 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**

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.

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

In one example, the temperature difference of the fluidisable particles between the fluidisable particle inlet (or the fluidisable particle and fluidisation gas inlet) of the fragmentation reactor and the fluidisable particle outlet of the fragmentation reactor is within the range of from 10 to 600°C, such as from 50 to 250°C, or from 50 to 150°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, the water content in the fluidisation gas is at least 50 wt.%, such as at least 60 wt.%, at least 70 wt.%, at least 75 wt.%, at least 80 wt.%, at least 85 wt.%, at least 90 wt.%, at least 95 wt.%, or at least 99 wt.%, based on the total weight of the fluidisation gas.

In one example, the water content in the fluidisation gas is no greater than 90 wt.%, such as no greater than 95 wt.%, no greater than 99 wt.%, or no greater than 99.5 wt.%, based on the total weight of the fluidisation gas.

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, the water content in the atomisation gas is at least 50 wt.%, such as at least 60 wt.%, at least 70 wt.%, at least 75 wt.%, at least 80 wt.%, at least 85 wt.%, at least 90 wt.%, at least 95 wt.%, or at least 99 wt.%, based on the total weight of the atomisation gas.

In one example, the water content in the atomisation gas is no greater than 90 wt.%, such as no greater than 95 wt.%, no greater than 99 wt.%, or no greater than 99.5 wt.%, based on the total weight of the atomisation gas.

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 fluidisation gas.

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

In one example, the mass ratio of the total amount of sugar introduced into the reactor to the total amount of water introduced into the reactor is at least 0.1:1, such as at least 0.2:1, at least 0.3:1, at least 0.4:1, at least 0.45:1, at least 0.5:1, at least 0.55:1, at least 0.6:1, at least 0.65:1, at least 0.7:1, at least 0.75:1, at least 0.8:1, at least 0.85:1, at least 0.9:1, or at least 0.95:1.

In one example, the mass ratio of the total amount of sugar introduced into the reactor to the total amount of water introduced into the reactor is no greater than 5:1, such as no greater than 4:1, no greater than 3.5:1, no greater than 3:1, no greater than 2.5:1, no greater than 2:1, no greater than 1.5:1, no greater than 1.4:1, no greater than 1.3:1, no greater than 1.25:1, no greater than 1.2:1, no greater than 1.15:1, no greater than 1.1:1, no greater than 1.05:1, or no greater than 1:1.

In one example, the mass ratio of the total amount of sugar introduced into the reactor to the total amount of water introduced into the reactor is from 0.2:1 to 5:1, such as from 0.25:1 to 4:1, from 0.25:1 to 3.5:1 from 0.25:1 to 2.2:1, from 0.3:1 to 1.8:1, from 0.4:1 to 1.75:1, from 0.55:1 to 1.5:1, from 0.6:1 to 1.3:1, from 0.65:1 to 1.2:1, from 0.7:1 to 1:1, or from 0.75:1 to 0.90:1.

In one example, the mass ratio of water introduced into the reactor via the feedstock solution to the total amount of water introduced into the reactor is at least 0.001:1, such as at least 0.005:1, at least 0.01:1, at least 0.02:1, at least 0.04:1, at least 0.05:1, at least 0.1:1, at least 0.15:1, at least 0.2:1, at least 0.25:1, or at least 0.3:1.

In one example, the mass ratio of water introduced into the reactor via the feedstock solution to the total amount of water introduced into the reactor is no greater than 5:1, such as no greater than 4:1, no greater than 3:1, no greater than 2:1, no greater than

1:1, no greater than 0.8:1, no greater than 0.6:1, no greater than 0.55:1, no greater than 0.5:1, no greater than 0.45:1, or no greater than 0.4:1.

In one example, the mass ratio of water introduced into the reactor via the feedstock solution to the total amount of water introduced into the reactor is from 0.2:1 to 3:1, such as from 0.04:1 to 4:1, from 0.05:1 to 2:1, from 0.1 to 1:1, from 0.15:1 to 0.6:1, from 0.2:1 to 0.5:1, from 0.25:1 to 0.45:1, or from 0.3:1 to 0.4:1.

**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 d) comprises separating solids from the solids-dense fragmentation product 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” herein 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 (d) (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.

**Water content in vol.%**

In one example, the water content is based on all gas phase constituents at the outlet of the reactor.

In one example, the water content is based on all gas phase constituents within the reactor.

In one example, the water content is measured (e.g. using suitable instrumentation). Suitable instrumentation for measuring water content will be known to those skilled in the art.

In one example, the water content is calculated (e.g. theoretically determined). Suitable means of calculating water content will be known to those skilled in the art.

As explained in “d) separating solids from the fragmentation product” below, in one example, step d) comprises separating the solids from the fragmentation product using a physical separation device.

In one example, where a physical separation device (e.g. a filter) is used, the water content is based on all gas phase constituents at an inlet of the physical separation device (e.g. a filter).

In one example, the water content at least 45 vol.%, such as at least 50 vol.%, at least 55 vol.%, at least 60 vol.%, at least 65 vol.%, at least 70 vol.%, at least 75 vol.%, or at least 80 vol.% based on all gas phase constituents.

In one example, the water content at the outlet of the reactor is at least 45 vol.%, such as at least 50 vol.%, at least 55 vol.%, at least 60 vol.%, at least 65 vol.%, at least 70 vol.%, at least 75 vol.%, or at least 80 vol.%, based on all gas phase constituents at the outlet of the reactor.

In one example, the water content within the reactor is at least 45 vol.%, such as at least 50 vol.%, at least 55 vol.%, at least 60 vol.%, at least 65 vol.%, at least 70 vol.%, at least 75 vol.%, or at least 80 vol.%, based on all gas phase constituents within the reactor.

In one example, the water content at the inlet of the physical separation device (e.g. filter) is at least 45 vol.%, such as at least 50 vol.%, at least 55 vol.%, at least 60 vol.%, at

least 65 vol.%, at least 70 vol.%, at least 75 vol.%, or at least 80 vol.%, based on all gas phase constituents at the inlet of the physical separation device.

In one example, the water content is no greater than 99 vol.%, such as no greater than 95 vol.%, no greater than 90 vol.%, no greater than 85 vol.%, or no greater than 80 vol.%, based on all gas phase constituents.

In one example, the water content at the outlet of the reactor is no greater than 99 vol.%, such as no greater than 95 vol.%, no greater than 90 vol.%, no greater than 85 vol.%, or no greater than 80 vol.%, based on all gas phase constituents at the outlet of the reactor.

In one example, the water content within the reactor is no greater than 99 vol.%, such as no greater than 95 vol.%, no greater than 90 vol.%, no greater than 85 vol.%, or no greater than 80 vol.%, based on all gas phase constituents within the reactor.

In one example, the water content at the inlet of the physical separation device (e.g. filter) is no greater than 99 vol.%, such as no greater than 95 vol.%, no greater than 90 vol.%, no greater than 85 vol.%, or no greater than 80 vol.%, based on all gas phase constituents at the inlet of the physical separation device.

In one example, the water content is from 45 to 99.5 vol.%, such as from 50 to 99 vol.%, from 55 to 97.5 vol.%, from 60 to 92.5 vol.%, from 65 to 90 vol.%, from 70 to 87.5 vol.%, or from 75 to 85 vol.%, based on all gas phase constituents.

In one example, the water content at the outlet of the reactor is from 45 to 99.5 vol.%, such as from 50 to 99 vol.%, from 55 to 97.5 vol.%, from 60 to 92.5 vol.%, from 65 to 90 vol.%, from 70 to 87.5 vol.%, or from 75 to 85 vol.%, based on all gas phase constituents at the outlet of the reactor.

In one example, the water content within the reactor is from 45 to 99.5 vol.%, such as from 50 to 99 vol.%, from 55 to 97.5 vol.%, from 60 to 92.5 vol.%, from 65 to 90 vol.%, from 70 to 87.5 vol.%, or from 75 to 85 vol.%, based on all gas phase constituents within the reactor.

In one example, the water content at the inlet of the physical separation device (e.g. filter) is from 45 to 99.5 vol.%, such as from 50 to 99 vol.%, from 55 to 97.5 vol.%, from 60 to

92.5 vol.%, from 65 to 90 vol.%, from 70 to 87.5 vol.%, or from 75 to 85 vol.%, based on all gas phase constituents at the inlet of the physical separation device.

**Partial pressure**

In one example, the partial pressure of steam is greater than 650 mbar.

The present inventors have also found that the presence of steam at a partial pressure of greater than 650 mbar helps to reduce the amount of such solids being transported downstream of the reactor and negatively affecting equipment.

In one example, the partial pressure of steam is at an outlet of the reactor.

In one example, the partial pressure of steam is within the reactor.

In one example, where a physical separation device (e.g. a filter) is used, the partial pressure is at the physical separation device (e.g. an inlet thereof).

As will be understood by those skilled in the art, the partial pressure of a gas may be defined by the below formula:

$$p_i = x_i \times p$$

in which $p_i$ is the partial pressure of a component in a gas mixture, $x_i$ is the volume fraction of the component in the gas mixture, and p is the total pressure of the gas mixture.

In one example, the partial pressure is measured (e.g. using suitable instrumentation). Suitable instrumentation for measuring partial pressure will be known to those skilled in the art.

In one example, the partial pressure is calculated (e.g. theoretically determined). Suitable means of calculating partial pressure will be known to those skilled in the art.

In one example, the partial pressure of steam is at least 700 mbar, such as at least 750 mbar, at least 800 mbar, at least 850 mbar, at least 900 mbar, at least 950 mbar, at least 1000 mbar, at least 1050 mbar, at least 1100 mbar, at least 1150 mbar, at least 1200

mbar, at least 1250 mbar, at least 1300 mbar, at least 1350 mbar, at least 1400 mbar, at least 1450 mbar, at least 1500 mbar, at least 1550 mbar, at least 1600 mbar, at least 1650 mbar, at least 1700 mbar, at least 1750 mbar, at least 1800 mbar, at least 1850 mbar, at least 1900 mbar, at least 1950 mbar, at least 2000 mbar, at least 2050 mbar, at least 2100 mbar, at least 2150 mbar, or at least 2200 mbar.

In one example, the partial pressure of steam at the outlet of the reactor is greater than 650 mbar. In one example, the partial pressure of steam at the outlet of the reactor is at least 700 mbar, such as at least 750 mbar, at least 800 mbar, at least 850 mbar, at least 900 mbar, at least 950 mbar, at least 1000 mbar, at least 1050 mbar, at least 1100 mbar, at least 1150 mbar, at least 1200 mbar, at least 1250 mbar, at least 1300 mbar, at least 1350 mbar, at least 1400 mbar, at least 1450 mbar, at least 1500 mbar, at least 1550 mbar, at least 1600 mbar, at least 1650 mbar, at least 1700 mbar, at least 1750 mbar, at least 1800 mbar, at least 1850 mbar, at least 1900 mbar, at least 1950 mbar, at least 2000 mbar, at least 2050 mbar, at least 2100 mbar, at least 2150 mbar, or at least 2200 mbar.

In one example, the partial pressure of steam within the reactor is greater than 650 mbar. In one example, as the partial pressure of steam within the reactor is at least 700 mbar, such as at least 750 mbar, at least 800 mbar, at least 850 mbar, at least 900 mbar, at least 950 mbar, at least 1000 mbar, at least 1050 mbar, at least 1100 mbar, at least 1150 mbar, at least 1200 mbar, at least 1250 mbar, at least 1300 mbar, at least 1350 mbar, at least 1400 mbar, at least 1450 mbar, at least 1500 mbar, at least 1550 mbar, at least 1600 mbar, at least 1650 mbar, at least 1700 mbar, at least 1750 mbar, at least 1800 mbar, at least 1850 mbar, at least 1900 mbar, at least 1950 mbar, at least 2000 mbar, at least 2050 mbar, at least 2100 mbar, at least 2150 mbar, or at least 2200 mbar.

In one example, the partial pressure of steam at the inlet of the physical separation device (e.g. filter) is greater than 650 mbar. In one example, the partial pressure of steam at the inlet of the physical separation device (e.g. filter) is at least 700 mbar, such as at least 750 mbar, at least 800 mbar, at least 850 mbar, at least 900 mbar, at least 950 mbar, at least 1000 mbar, at least 1050 mbar, at least 1100 mbar, at least 1150 mbar, at least 1200 mbar, at least 1250 mbar, at least 1300 mbar, at least 1350 mbar, at least 1400 mbar, at least 1450 mbar, at least 1500 mbar, at least 1550 mbar, at least 1600 mbar, at least 1650 mbar, at least 1700 mbar, at least 1750 mbar, at least 1800 mbar, at least 1850 mbar, at least 1900 mbar, at least 1950 mbar, at least 2000 mbar, at least 2050 mbar, at least 2100 mbar, at least 2150 mbar, or at least 2200 mbar.

In one example, the partial pressure of steam is no greater than 5000 mbar, such as no greater than 4500 mbar, no greater than 4000 mbar, no greater than 3800 mbar, no greater than 3600 mbar, no greater than 3400 mbar, no greater than 3200 mbar, no greater than 3000 mbar, no greater than 2800 mbar, no greater than 2600 mbar, or no greater than 2500 mbar.

In one example, the partial pressure of steam at the outlet of the reactor is no greater than 5000 mbar, such as no greater than 4500 mbar, no greater than 4000 mbar, no greater than 3800 mbar, no greater than 3600 mbar, no greater than 3400 mbar, no greater than 3200 mbar, no greater than 3000 mbar, no greater than 2800 mbar, no greater than 2600 mbar, or no greater than 2500 mbar.

In one example, the partial pressure of steam within the reactor is no greater than 5000 mbar, such as no greater than 4500 mbar, no greater than 4000 mbar, no greater than 3800 mbar, no greater than 3600 mbar, no greater than 3400 mbar, no greater than 3200 mbar, no greater than 3000 mbar, no greater than 2800 mbar, no greater than 2600 mbar, or no greater than 2500 mbar.

In one example, the partial pressure of steam at the inlet of the physical separation device (e.g. filter) is no greater than 5000 mbar, such as no greater than 4500 mbar, no greater than 4000 mbar, no greater than 3800 mbar, no greater than 3600 mbar, no greater than 3400 mbar, no greater than 3200 mbar, no greater than 3000 mbar, no greater than 2800 mbar, no greater than 2600 mbar, or no greater than 2500 mbar.

In one example, the partial pressure of steam is from 700 to 5000 mbar, such as from 750 to 4000 mbar, from 800 to 3500 mbar, from 1000 to 3000 mbar, from 1200 to 2800 mbar, from 1500 to 2700 mbar, or from 2000 to 2500 mbar.

In one example, the partial pressure of steam at the outlet of the reactor is from 700 to 5000 mbar, such as from 750 to 4000 mbar, from 800 to 3500 mbar, from 1000 to 3000 mbar, from 1200 to 2800 mbar, from 1500 to 2700 mbar, or from 2000 to 2500 mbar.

In one example, the partial pressure of steam within the reactor is from 700 to 5000 mbar, such as from 750 to 4000 mbar, from 800 to 3500 mbar, from 1000 to 3000 mbar, from 1200 to 2800 mbar, from 1500 to 2700 mbar, or from 2000 to 2500 mbar.

In one example, the partial pressure of steam at the inlet of the physical separation device (e.g. filter) is from 700 to 5000 mbar, such as from 750 to 4000 mbar, from 800 to 3500 mbar, from 1000 to 3000 mbar, from 1200 to 2800 mbar, from 1500 to 2700 mbar, or from 2000 to 2500 mbar.

**d) separating solids from the fragmentation product**

The process comprises separating solids from the fragmentation product, wherein the solids comprise solids selected from the fluidisable particles, fragments of the fluidisable particles, by-products from the thermolytic fragmentation of the feedstock solution, and mixtures thereof.

In one example, 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, step d) 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 based on the total weight of the solids.

In one example, step d) comprises separating a major portion of the solids from the fragmentation product.

In one example, 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, step d) comprises separating substantially all of the solids from the fragmentation product.

In one example, step d) comprises separating the solids from the fragmentation product 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, step d) occurs downstream of the reactor.

In one example, the physical separation device is arranged downstream of the reactor.

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

In one example, step d) comprises filtering the fragmentation product using a filter.

In one example, the temperature at an inlet of the filter is from 230 to 390°C, or from 270 to 390°C, from 300 to 380°C, or from 330 to 370°C.

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. The filter efficiency may be measured using ASTM 795 ACFTD.

In one example, the method is suitable for industrial scale production of C1-C3 oxygenates.

**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 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 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 method 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 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; and

c) a separation device configured to separate solids from the 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;

wherein the temperature of the fragmentation product at an outlet of the reactor is at least 250°C, such as at least 300°C, at least 350°C, at least 400°C, or at least 450°C, and

wherein the water content is at least 40 vol.%, based on all gas phase constituents.

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) 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; and

c) a separation device configured to separate solids from the 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;

wherein the temperature of the fragmentation product at an outlet of the reactor is at least 250°C, such as at least 300°C, at least 350°C, at least 400°C, or at least 450°C, and

wherein the partial pressure of steam is greater than 650 mbar.

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 variation in pressure drop across the filter of a system according to embodiment of the invention;

Fig. 7 shows a schematic diagram of a candle filter; and