CONTINUOUS COUNTERFLOW REACTOR

The present patent disclosure concerns a method and a counterflow reactor system for allowing an abrasive slurry to react with a fluid.

Reactions between abrasive slurries and fluids normally need mixing to be efficient. As a consequence, the reactor systems, the reactor and components inside the reactor used during the processing are exposed to the moving abrasive slurry and, thus, are subjected to continuous wear and require maintenance and/or replacement.

Furthermore, the efficiency of the reactions between abrasive slurries and fluids typically increases with the mixing rate and therefore also result in higher maintenance of the equipment.

Reactions between abrasive slurries and fluids have lately received increased attention for example due to the possibility to reduce the carbon dioxide concentration in the earth's atmosphere by reactions with minerals, so called mineral carbonation. Some of the minerals that are relevant for mineral carbonation are silicates and/or carbonates, such as olivine, wollastonite, serpentine or steel slag which can react with carbon dioxide to form carbonate materials. However, the reaction rate between these minerals and carbon dioxide is low at ambient conditions, and the rate is influenced by temperature, pressure and pH.

One way to accelerate the reaction rate is by allowing slurries comprising the minerals to react with fluids comprising the carbon dioxide. These slurries facilitate the mixing and handling of the carbon dioxide and the mineral as well as allow control of the reaction within relevant conditions. The reaction rate can further increase by altering the reaction conditions, such as temperature and pressure.

Additionally, the reactions for mineral carbonation may be exothermic or endothermic and the temperature in the reactor may need to be balanced during the processing.

Reactors typically used for mineral carbonation comprises moving parts to mix the abrasive slurries as well as piping to control the reactor temperature.

Thus, there are drawbacks associated with the reactor systems traditionally used for the reactions between abrasive slurries and fluids.

It is an object, among objects, of the present patent disclosure to overcome the drawbacks of the prior art and improve the reactor systems and methods for allowing abrasive slurries to react with fluids.

According to a first aspect, there is provided a method in a counterflow reactor system for allowing an abrasive slurry to react with a fluid, the counterflow reactor system comprising a counterflow reactor comprising a slurry inlet at a first side of the counterflow reactor, a slurry outlet at a second side of the counterflow reactor, opposite the first side, and a fluid inlet. The method comprising the steps of introducing an abrasive slurry into the counterflow reactor through the slurry inlet, introducing a fluid into the counterflow reactor through the fluid inlet, allowing the abrasive slurry to flow through the counterflow reactor from the slurry inlet towards the slurry outlet, and allowing at least a part of the introduced fluid to counterflow with respect to the flow of the abrasive slurry, and to react with the abrasive slurry.

By allowing a counterflow of the fluid with respect to the flow of the abrasive slurry, the particles of the abrasive slurry get exposed to the fluid and the fluid may dissolve in the abrasive slurry which improves the reaction rate. The method also keeps solids in suspension and reduces the settling inside the counterflow reactor. Additionally, the counterflow of the fluid with respect to the flow of the abrasive slurry confines the volume comprising the fluid. By confining the volume comprising fluid, the wear of for example pumps is reduced.

In some embodiments of the present disclosure, the fluid inlet is arranged at the second side of the counterflow reactor.

In some embodiments, the fluid is a gas or a supercritical fluid. In some embodiments, the gas or supercritical fluid is carbon dioxide. In some embodiments, the abrasive slurry comprises silicates and/or carbonates. In some embodiments, the abrasive slurry comprises olivine, wollastonite, serpentine and/or steel slag. In some embodiments, the abrasive slurry comprises water. In some embodiments, the slurry comprises additives. In some embodiments, the slurry optionally comprises between 0 – 10 wt% additives. In some embodiments, the additives are selected from sodium bicarbonate, ascorbic acid, oxalic acid or a combination thereof. In some embodiments, the abrasive slurry, comprises 10-45 wt%, or 15-40 wt%, of the olivine, wollastonite, serpentine, and/or steel slag, 0 – 10 wt% additives, and water, where wt% is relative to a total weight of the abrasive slurry. The abrasive slurry may further comprise dissolved species, for example magnesium ions or calcium ions, and carbonate ions. The olivine, wollastonite, serpentine and/or steel slag are present as solid particles. These minerals comprise one or more of the (metal) silicates and, after reacting with carbon dioxide, one or more carbonates. When minerals like olivine are exposed to air and water, there may be some metal carbonate(s) present already in the mined mineral.

Embodiments of the present disclosure may include reaction conditions. In some embodiments, the temperature of the counterflow reactor lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid and the abrasive slurry is exothermic.

In some embodiments, the method may include the steps of allowing at least a part of the abrasive slurry to flow from the slurry outlet of the counterflow reactor to a heat exchanger configured to cool the abrasive slurry, and allowing the abrasive slurry to flow from the heat exchanger into the counterflow reactor through the slurry inlet, wherein the heat exchanger is arranged external to the counterflow reactor. As will be understood, a remainder of the abrasive slurry that is not led to the heat exchanger may be taken out of the reactor, or more generally out of the circulating slurry, and be further processed, such as drying, to form a product material. An amount of unreacted abrasive slurry is added to compensate for the remainder of the abrasive slurry that is taken out and is allowed mix with the at least the part of the abrasive slurry flowing to or from the heat exchanger and to flow to the counterflow reactor for reacting with the fluid. The amount of unreacted abrasive slurry added is preferably equal to the remainder of the slurry that is taken out, in order to keep the slurry level in the reactor substantially constant, substantially here indicating allowing for variations of at most 20%, or at most 10%, or even at most 5%, of the slurry level relative to a total length of the reactor.

One way to achieve the substantially constant slurry level in the reactor is by the use of one or more suitable respective flow controllers or controllable valves arranged to control the flow of the remainder of the abrasive slurry, the unreacted abrasive slurry added, or both.

In some embodiments, the slurry inlet is arranged such that the abrasive slurry is introduced into the counterflow reactor at a slurry inlet level. The slurry inlet level may, in some embodiments, be equal to, above, or slightly above (e.g. at most 10 cm) the slurry level. The slurry inlet level may alternatively be below the slurry level or slightly below (e.g. at most 10 cm) the slurry level.

In some embodiments, the slurry inlet may be an end of a slurry inlet pipe through which the abrasive slurry is able to flow, wherein the slurry inlet pipe extends into the reactor. The slurry inlet pipe may extend into the reactor from a lateral side of the reactor, or from a longitudinal end of the reactor. The pipe may optionally extend from the second side of the reactor. The slurry inlet may, in some embodiments, be directed in a downward direction, with a normal direction having an angle of less than 90° with respect to the central axis. In some embodiments, the normal of the slurry inlet is parallel to the central axis. In other embodiments, the normal of the slurry inlet has an angle that is at least 45° relative to the central axis. The angle may be between 80° and 100°, such as 90° (normal of the slurry inlet perpendicular to the central axis).

In some embodiments, the reactor may comprise a slurry receiving surface, or splash surface, arranged to receive any abrasive slurry flowing in a direction other than a direction towards the second side of the reactor. This may be abrasive slurry droplets that would otherwise possibly cause abrasion of, for example, reactor walls. The slurry receiving surface is arranged such that the abrasive slurry is directed towards the second side of the reactor. The slurry receiving surface may direct a majority of the flow, or the entire flow, of the abrasive slurry flowing to the first slurry inle towards the second side of the reactor. In other words, towards the abrasive slurry in the reactor. When the normal of the slurry inlet is directed in a downward direction, the splash surface may be positioned around the slurry inlet, such as with a conical shape that widens in a direction towards the second side of the reactor, to receive any slurry splashing upwards towards other parts of the reactor, such as walls. This allows the abrasion of other parts of the reactor, such as reactor walls, to be reduced.

When a large part of the slurry flow contacts the slurry receiving surface, this may furthermore aid the reaction by comminution of the particles in the slurry, thus creating a larger surface area of the carbon dioxide to react with the species in the particles that are reactive to carbon dioxide. In embodiments where a large part, or the entire slurry flow is received by the slurry receiving surface, for example when the normal of the slurry inlet is perpendicular to the central axis, the slurry receiving surface may be positioned such that the slurry is directed at least partially, or entirely, in a downward direction parallel to the central axis towards the slurry at the slurry level and below. This protects the walls and may further cause mixing eddies/currents to be present within the slurry in the reactor, aiding the reaction.

The splash surface is preferably made of an abrasion resistant material, such as is hardened steels (such as AR400 or AR500), stainless steel (such as duplex, 301, 201, 431, NITRONIC 30, or NITRONIC 60 stainless steel), ceramics (such as alumina, silicon nitride, sialon, silicon carbide, boron carbide, or zirconia), and metal carbides (such as tungsten carbide or titanium carbide). The splash surface may optionally be comprised in a splash plate. Such a splash plate may optionally be entirely made of the abrasion resistant material.

The use of the heat exchanger allows the temperature of the abrasive slurry to be controlled and internal counterflow reactor features, such as pipes comprising cooling agent, are redundant. By avoiding these internal features, the abrasion of the counterflow reactor is reduced. In other words, the counterflow reactor, when not in use, is substantially empty inside. When in use, a relatively low surface area is in contact with the flowing abrasive slurry. The counterflow reactor in such an embodiment comprises inner walls defining an internal reactor volume, of which a portion that is below a slurry level has at least 85%, preferably 90%, by volume arranged to receive the abrasive slurry and/or the fluid, like carbon dioxide.

In some embodiments, the heat exchanger comprises one or more elongated sections wherein the elongated sections are arranged generally vertical and wherein the elongated sections are cooled by a cooling agent, and wherein the method comprises the step of allowing the abrasive slurry to flow through the elongated sections.

This prevents settling of solids in the heat exchanger and the generally vertical arrangement improves the space utilization of the production plant.

In some embodiments, the method comprises the step of agitating at least a part of the abrasive slurry flowing from the slurry outlet of the counterflow reactor using an agitation device and allowing the agitated abrasive slurry to flow towards the slurry inlet.

This disrupts possible passivation layers on the particle surfaces of the abrasive slurry and improves the reaction yield.

In some embodiments, the abrasive slurry is allowed to flow in a downward direction, and the fluid is allowed to flow in an upward direction inside the counterflow reactor.

This further prevent settling of solids inside the counterflow reactor. It further facilitates the confinement of the volume comprising the fluid, thus, reducing the wear of the counterflow reactor system.

In some embodiments, the fluid inlet is a nozzle positioned at the first side of the counterflow reactor, and the method comprises introducing the fluid through the fluid inlet in a downward direction and allowing at least a part of the fluid to flow in an upward direction.

This maximizes the duration that the fluid spends in contact with the abrasive slurry. Additionally, since the fluid is allowed to react with the abrasive slurry the part of the fluid which is allowed to flow in an upward direction is smaller than the part introduced in the downward direction resulting in a net downward force acting on the abrasive slurry. The net downward force promotes the flow of the abrasive slurry and reduce the input energy required for flowing the abrasive slurry.

In some embodiments, the counterflow reactor further comprises a fluid outlet positioned at the first side of the counterflow reactor, wherein the slurry inlet is distanced from the fluid outlet in a direction towards the second side of the counterflow reactor, the method comprising allowing unreacted fluid to flow out of the counterflow reactor through the fluid outlet, and reintroducing at least a part of the fluid flowing out of the fluid outlet to the counterflow reactor via the fluid inlet.

This allows excess fluid to be reused and increase the yield.

In some embodiments, the counterflow reactor comprises a plurality of fluid inlets, the method comprises introducing the fluid into the counterflow reactor through each fluid inlet of the plurality of fluid inlets.

A plurality of fluid inlets facilitates that the particles of the abrasive slurry get exposed to the fluid, dissolution of the fluid in the abrasive slurry, keeping solids in suspension and reduce the settling inside the counterflow reactor. Additionally, it confines the volume comprising the fluid since the flow of the fluid can be controlled, resulting in better overall control of the volume comprising the fluid.

In some embodiments, the fluid inlets are arranged at different distances between the first side and the second side of the counterflow reactor.

The fluid inlets arranged at different distances creates a more stable fluid content in the reactor over the whole volume. Since fluid is consumed by the reaction by the reaction with the abrasive slurry, a plurality of fluid inlets arranged at different distances between the first side and the second side enables a smaller concentration gradient. It further facilitates that the particles of the abrasive slurry get exposed to the fluid, dissolution of the fluid in the abrasive slurry, keeping solids in suspension and reduce the settling inside the counterflow reactor. Additionally, it confines the volume comprising the fluid since the flow of the fluid can be distributed, resulting in better overall control of the volume comprising the fluid.

In some embodiments, the abrasive slurry comprises silicates and/or carbonates and water, and wherein the fluid comprises carbon dioxide, and wherein the input mass ratio of the flow of the silicates and/or carbonates is between 15 – 35 wt% with respect to the sum of input silicates and/or carbonates, water and carbon dioxide to the counterflow reactor. In some embodiments, the input mass ratio of the flow of the water is between 40 – 75 wt% with respect to the sum of input silicates and/or carbonates, water and carbon dioxide to the counterflow reactor. In some embodiments, the input mass ratio of the flow of the carbon dioxide is between 10 – 25 wt% with respect to the sum of input silicates and/or carbonates, water and carbon dioxide to the counterflow reactor. Input mass ratios within the above specified ranges further improves the yield of the reaction.

Optionally, in some embodiments, the slurry outlet is a first slurry outlet and the counterflow reactor comprises a second slurry outlet arranged to output slurry from the counterflow reactor. Furthermore, the slurry inlet is a first slurry inlet and the counterflow reactor system comprises a second slurry inlet for providing unreacted abrasive slurry to the counterflow reactor. This is one way for continuous addition of unreacted abrasive slurry and removal of reacted abrasive slurry.

Optionally, in some embodiments, the unreacted abrasive slurry comprises 40 to 90 wt% water per weight of the unreacted abrasive slurry, and 0 to 10 wt% additives per weight of the abrasive slurry.

Furthermore, the unreacted abrasive slurry may comprise 10 to 40 wt% per weight of the unreacted abrasive slurry of metal silicate and dissolved metal ions; and 0 to 55 wt% of one or more non-reactive species per weight of a sum of the metal silicate, dissolved metal ions and the non-reactive species.

The non-reactive species may be or comprise minerals non-reactive to the fluid, in particular carbon dioxide. The non-reactive species may partially dissolve into the water.

Such an abrasive slurry improves the efficiency of the reaction between the abrasive slurry and the fluid, because it has a relatively high slurry density. It is beneficial if there is at most 40 wt%, or 30 wt% or 20 wt%, or even less, of the one or more non-reactive species. The higher the slurry density, the lower the total volume requiring handling in the reactor system, like pumping, and outside the reactor system, such as filtering, drying, etc.

Optionally, in some embodiments, the metal silicate comprises magnesium silicate, and the dissolved metal ions comprise magnesium ions.

Optionally, in some embodiments, the amount of carbon dioxide in the reactor is between 20 to 60 wt%, such as 30 to 50 wt%, per total weight of the carbon dioxide and the abrasive slurry in the reactor. This allows for high yields to be achieved, of over 70% or even 80% relative to the silicate species reactive to olivine, such as magnesium silicate. Most of the carbon dioxide is present in the gas or supercritical phase, while between 2 and 10% of the carbon dioxide in the reactor is dissolved in the abrasive slurry when the abrasive slurry is an aqueous abrasive slurry.

Optionally, in some embodiments, the unreacted abrasive slurry comprises particles with an a size of at most 100 μm, such as having an average particle size in the range of 5 to 65 μm. This further improves the efficiency of the reaction between the abrasive slurry and the fluid.

Optionally, in some embodiments, the unreacted abrasive slurry comprises olivine, wollastonite, serpentine and/or steel slag, preferably olivine.

Optionally, in some embodiments, the abrasive slurry is an aqueous abrasive slurry comprising water.

Optionally, in some embodiments, the abrasive slurry is an aqueous abrasive slurry comprising 40 to 90 wt% water per weight of the abrasive slurry, 0 to 10 wt% additives per weight of the abrasive slurry.

Furthermore, the aqueous abrasive slurry comprises 10 to 40 wt% per weight of the abrasive slurry of: metal silicate, metal carbonate, silica, dissolved metal ions, and 0 to 55 wt% of one or more non-reactive species per weight of a sum of the metal silicate, metal carbonate, silica, dissolved metal ions and the non-reactive species. Such an abrasive slurry improves the efficiency of the reaction between the abrasive slurry and the fluid, because it has a relatively high slurry density. It is beneficial if there is at most 40 wt%, or 30 wt% or 20 wt%, or even less, of the one or more non-reactive species. The higher the slurry density, the lower the total volume requiring handling in the reactor system, like pumping, and outside the reactor system, such as filtering, drying, etc.

The non-reactive species may be or comprise minerals non-reactive to the fluid, in particular carbon dioxide. The non-reactive species may partially dissolve into the water. Optionally, in some examples, the metal silicate comprises magnesium silicate, the metal carbonate comprises magnesium carbonate, and the dissolved metal ions comprise magnesium ions. Optionally, in some examples, the amount of carbon dioxide in the reactor is between 10 to 25 wt% per total weight of the carbon dioxide in the reactor and the abrasive slurry in the reactor. Optionally, in some examples, the abrasive slurry comprises particles with a size between 5 – 65 µm. This further improves the efficiency of the reaction between the abrasive slurry and the fluid. Preferably the abrasive slurry comprises particles with a size between 10 – 60 µm, more preferably between 15 – 55 µm.

In some embodiments, the abrasive slurry optionally comprises 0-10 wt% additives with respect to mass of the abrasive slurry. In some embodiments, the additives are selected from sodium bicarbonate, ascorbic acid and oxalic acid. These additives may further improve the yield of the reaction.

In some embodiments, the input mass ratio of the flow of the silicates and/or carbonates is 17 wt%, the input mass ratio of the flow of carbon dioxide is 13 wt%, and the input mass ratio of the flow of the water is 70 wt%. In some embodiments, the silicates and/or carbonates comprises olivine.

In some embodiments, the input mass ratio of the flow of the silicates and/or carbonates is 32 wt%, the input mass ratio of the flow of carbon dioxide is 21 wt%, and the input mass ratio of the flow of the water is 47 wt%.

In some embodiments, the counterflow reactor extends longitudinally along a central axis and comprises a first longitudinal end at the first side and a second longitudinal end at the second side.

In some embodiments, the counterflow reactor comprises a first cross-sectional area at the first side, a second cross-sectional area at the second side, and a third cross-sectional area between the first longitudinal end and the second longitudinal end, wherein the first cross-sectional area the second cross-sectional area and the third cross-sectional area each extend perpendicular to the central axis, and the first cross-sectional area is a first inner cross-sectional area of the counterflow reactor, the second cross-sectional area is a second inner cross-sectional area of the counterflow reactor, and the third cross-sectional area is a third inner cross-sectional area of the counterflow reactor.

In some embodiments, the first cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a first widened section having the first cross-sectional area, the first widened section extending partially along the counterflow reactor from the first longitudinal end towards the second longitudinal end.

A larger first cross-sectional area than the third cross-sectional area helps to counter erosion of the reactor.

In some embodiments, the second cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a second widened section having the second cross-sectional area, the second widened section extending partially along the counterflow reactor from the second longitudinal end towards the first longitudinal end.

A second cross-sectional area larger than the third cross-sectional area helps to counter erosion of the reactor. The flow speed of the slurry is lower at the second widened section and allow the fluid to rise upwards and allow most of the fluid to stay in the counterflow reactor itself.

In some embodiments, the counterflow reactor comprises the first widened section and the second widened section, wherein the counterflow reactor comprises a neck having the third cross-sectional area.

A first cross-sectional area larger than the third cross-sectional area helps to counter erosion of the reactor.

In some embodiments, the ratio between the first cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.2 and 5, more preferably between 1.3 and 2.25.

In some embodiments, the fluid inlet is arranged through the vertical walls of the counterflow reactor.

This reduces the wear of the reactor.

In some embodiments, one or more agitation devices is configured to agitate the fluid in the counterflow reactor.

This accelerates the dissolution of the fluid in the abrasive slurry thereby increasing the yield.

In some embodiments, the ratio between the second cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.15 and 5, more preferably between 1.2 and 2.25.

A ratio between the second and third cross-sectional area between abovementioned ratio further helps to counter erosion and improves yield.

According to a second aspect, there is provided a counterflow reactor system for allowing an abrasive slurry to react with a fluid, wherein the counterflow reactor system comprises a counterflow reactor comprising a slurry inlet at a first side of the counterflow reactor, a slurry outlet at a second side of the counterflow reactor, opposite the first side, and a fluid inlet configured to introduce the fluid into the counterflow reactor and such that, when in use, at least a part of the introduced fluid flows in a direction opposite to a flow of the abrasive slurry.

By allowing at least a part of the fluid to flow in a direction opposite to a flow of the abrasive slurry, the particles of the abrasive slurry get exposed to the fluid and the fluid may dissolve in the abrasive slurry which improves the reaction rate. The method also keeps solids in suspension and reduce the settling inside the counterflow reactor. Additionally, the counterflow of the fluid with respect to the flow of the abrasive slurry confines the volume comprising the fluid. By confining the volume comprising fluid, the wear of for example pumps is reduced.

In some embodiments of the present disclosure, the counterflow reactor comprises a slanted bottom.

This prevents settling of solids in the counterflow reactor. Additionally, this further prevents zones with no flow of slurry in the reactor. Furthermore, if and/or when the flow of slurry is stopped, the slanted bottom enables solids to be flushed out of the reactor by applying a flow of fluid.

In some embodiments the slanted bottom comprises a membrane or mesh, with a plurality of openings forming the fluid inlets. This further improves the distribution of fluid over the cross-sectional area of the counterflow reactor, resulting in better overall control of the volume comprising the fluid.

In some embodiments, the fluid inlet comprises a nozzle arranged to inject the fluid in a downward direction into the counterflow reactor.

This maximizes the duration that the fluid spends in contact with the abrasive slurry. Additionally, since the fluid is allowed to react with the abrasive slurry the part of the fluid which is allowed to flow in an upward direction is smaller than the part introduced in the downward direction resulting in a net downward force acting on the abrasive slurry. The net downward force promotes the flow of the abrasive slurry and reduce the input energy required for flowing the abrasive slurry.

In some embodiments, the counterflow reactor system is adapted for pressures up to 130 bar and wherein the counterflow reactor is adapted for temperatures up to 250 °C.

These conditions increase the yield of the reaction. For some fluids these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the fluid inlet is arranged at the second side of the counterflow reactor.

In some embodiments, the counterflow reactor system further comprises a fluid outlet positioned at the first side of the counterflow reactor, wherein the slurry inlet is distanced from the fluid outlet in a direction towards the second side of the counterflow reactor, wherein the fluid outlet is in fluid connection with the fluid inlet of the counterflow reactor.

This allows excess fluid to be reused and increase the yield.

In some embodiments, the counterflow reactor system comprises a plurality of fluid inlets.

This further facilitate that the particles of the abrasive slurry get exposed to the fluid, dissolution of the fluid in the abrasive slurry, keeping solids in suspension and reduce the settling inside the counterflow reactor. Additionally, it confines the volume comprising the fluid since the flow of the fluid can be distributed, resulting in better overall control of the volume comprising the fluid.

In some embodiments, the counterflow reactor system comprises a plurality of fluid inlets wherein the fluid inlets are spaced from each other over a length of the counterflow reactor.

The fluid inlets spaced from each other creates a more stable fluid content in the reactor over the whole volume. Since fluid is consumed by the reaction by the reaction with the abrasive slurry, a plurality of fluid inlets arranged at different distances between the first side and the second side enables a smaller concentration gradient. This further facilitate that the particles of the abrasive slurry get exposed to the fluid, dissolution of the fluid in the abrasive slurry, keeping solids in suspension and reduce the settling inside the counterflow reactor. Additionally, it confines the volume comprising the fluid since the flow of the fluid can be distributed, resulting in better overall control of the volume comprising the fluid.

In some embodiments, the counterflow reactor system comprises one or more agitation devices configured to agitate the abrasive slurry and/or the fluid.

This improves the yield of the reaction by facilitating that the particles of the abrasive slurry get exposed to the fluid, dissolution of the fluid in the abrasive slurry, keeping solids in suspension and reduce the settling inside the counterflow reactor, as well as disrupting possible passivation layers on the particles of the abrasive slurry.

In some embodiments, the counterflow reactor system comprises one or more agitation devices configured to agitate the fluid in the counterflow reactor. The agitation device may be configured to agitate the fluid in the counterflow reactor may for this purpose use ultrasound.

This accelerates the dissolution of the fluid in the abrasive slurry thereby increasing the yield.

In some embodiments, the counterflow reactor system comprises one or more agitation devices arranged externally to the counterflow reactor and configured to agitate the slurry.

This disrupts possible passivation layers on the particle surfaces of the abrasive slurry and improves the reaction yield.

In some embodiments, the counterflow reaction system comprises a heat exchanger, wherein the heat exchanger is external to the counterflow reactor and in fluid communication with the slurry outlet.

This allows the temperature of the abrasive slurry to be controlled and internal counterflow reactor features, such as pipes comprising cooling agent, are redundant. By avoiding these internal features, the abrasion of the counterflow reactor is reduced.

In some embodiments, the heat exchanger comprises one or more elongated sections arranged generally vertically when the heat exchanger is in use, and arranged to allow the abrasive slurry to flow through the elongated sections and to be cooled by a cooling agent.

This prevents settling of solids in the heat exchanger and the generally vertical arrangement improves the space utilization of the production plant.

In some embodiments, the fluid inlet is arranged through the vertical walls of the counterflow reactor.

This reduces the wear of the counterflow reactor.

In some embodiments, the counterflow reactor extends longitudinally along a central axis and comprises a first longitudinal end at the first side and a second longitudinal end at the second side.

In some embodiments, the counterflow reactor comprises a first cross-sectional area at the first side, a second cross-sectional area at the second side, and a third cross-sectional area between the first longitudinal end and the second longitudinal end, wherein the first cross-sectional area the second cross-sectional area and the third cross-sectional area each extend perpendicular to the central axis, and the first cross-sectional area is a first inner cross-sectional area of the counterflow reactor, the second cross-sectional area is a second inner cross-sectional area of the counterflow reactor, and the third cross-sectional area is a third inner cross-sectional area of the counterflow reactor.

In some embodiments, the first cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a first widened section having the first cross-sectional area, the first widened section extending partially along the counterflow reactor from the first longitudinal end towards the second longitudinal end.

A larger first cross-sectional area than the third cross-sectional area helps to counter erosion of the reactor.

In some embodiments, the second cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a second widened section having the second cross-sectional area, the second widened section extending partially along the counterflow reactor from the second longitudinal end towards the first longitudinal end.

A second cross-sectional area larger than the third cross-sectional area helps to counter erosion of the reactor.

In some embodiments, the counterflow reactor comprises the first widened section and the second widened section, wherein the counterflow reactor comprises a neck having the third cross-sectional area.

A larger first cross-sectional area than the third cross-sectional area helps to counter erosion of the reactor. A second cross-sectional area larger than the third cross-sectional area helps to counter erosion of the reactor.

In some embodiments, the ratio between the first cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.2 and 5, more preferably between 1.3 and 2.25.

In some embodiments, the ratio between the second cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.15 and 5, more preferably between 1.2 and 2.25.

This further helps to counter erosion of the reactor.

Brief description of figures

The accompanying drawings are used to illustrate presently preferred non-limiting exemplary embodiments of devices of the present disclosure. The above and other advantages of the features and objects of the disclosure will become more apparent, and the aspects and embodiments will be better understood from the following detailed description when read in conjunction with the accompanying drawings, in which:

Figure 1 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 2 is a schematic drawing of a counterflow reactor system according to some embodiments of the present disclosure.

Figure 3 is a schematic drawing of a counterflow reactor system according to some embodiments of the present disclosure.

Figure 4 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 5 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 6 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 7 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 8 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 9 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 10 is a schematic drawing of a counterflow reactor system according to some embodiments of the present disclosure.

Figure 11 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 12 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 13 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 14 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Figure 15 is a schematic drawing of a counterflow reactor system according to some embodiments of the present disclosure.

Figure 16 is a schematic drawing of a counterflow reactor system according to some embodiments of the present disclosure.

Figure 17 is a schematic drawing of a counterflow reactor according to some embodiments of the present disclosure.

Detailed Description of Preferred Embodiments

Figure 1 is a schematic drawing of a counterflow reactor 100 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 100 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 100, a slurry outlet 130 at a second side 110 of the counterflow reactor 100, opposite the first side 105, and a fluid inlet 140. In the embodiment of Figure 1, the fluid inlet 140 is depicted as a sparger. The sparger comprises a plurality of fluid openings from which the fluid, such as carbon dioxide, is released as bubbles. In the embodiment of Figure 1, the fluid openings are pointed in a downward direction, that is, a direction parallel to a slurry flow direction. This beneficially reduces clogging of the sparger. The counterflow reactor system according to the present disclosure comprises a counterflow reactor 100 for allowing an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the temperature of the counterflow reactor 100 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 100 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 100 comprises a fluid outlet 180.

In some embodiments, the counterflow reactor 100 extends longitudinally along a central axis 137 and comprises a first longitudinal end 106 at the first side 105 and a second longitudinal end 111 at the second side 110.

In some embodiments, the counterflow reactor 100 comprises a first cross-sectional area 161 at the first side 105, a second cross-sectional area 162 at the second side 110, and a third cross-sectional area 163 between the first longitudinal end 106 and the second longitudinal end 111, wherein the first cross-sectional area 161 the second cross-sectional area 162 and the third cross-sectional area 163 each extend perpendicular to the central axis 137, and the first cross-sectional area 161 is a first inner cross-sectional area of the counterflow reactor, the second cross-sectional area 162 is a second inner cross-sectional area of the counterflow reactor, and the third cross-sectional area 163 is a third inner cross-sectional area of the counterflow reactor.

If a cylindrical shaped reactor is used as in the figures, the respective inner cross-sectional areas have associated respective first 161, second 162 and third 163 inner diameters.

In some embodiments, the slurry inlet 120 is arranged below a maximum slurry level 151 in the counterflow reactor 100.

Figure 2 is a schematic drawing of a counterflow reactor system 20 comprising a counterflow reactor 100 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 100 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 100, a slurry outlet 130 at a second side 110 of the counterflow reactor 100, opposite the first side 105, and a fluid inlet 140. The counterflow reactor system according to the present disclosure comprises a counterflow reactor 100 for allowing an abrasive slurry 150 to react with a fluid 155. In some embodiments, the counterflow reactor system comprises a heat exchanger 260 configured to cool the abrasive slurry 150. The heat exchanger 260 is external to the counterflow reactor 100. Furthermore, in some embodiments the heat exchanger 260 comprises elongated sections 261 arranged generally vertically when the heat exchanger 260 is in use, and arranged to allow the abrasive slurry 150 to flow through the elongated sections 261 and to be cooled by a cooling agent 262. In some embodiments, a pump 270 is used to induce a flow of the slurry 150.

In some embodiments, the temperature of the counterflow reactor 100 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 100 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 100 comprises a fluid outlet 180.

Figure 3 is a schematic drawing of a counterflow reactor system 30 comprising a counterflow reactor 100 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 100 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 100, a slurry outlet 130 at a second side 110 of the counterflow reactor 100, opposite the first side 105, and a fluid inlet 140. The counterflow reactor system 30 according to the present disclosure comprises a counterflow reactor 100 for allowing an abrasive slurry 150 to react with a fluid 155. In some embodiments, the counterflow reactor system 30 comprises a heat exchanger 260 configured to cool the abrasive slurry 150. The heat exchanger 260 is external to the counterflow reactor 100. Furthermore, in some embodiments the heat exchanger comprises elongated sections 261 arranged to allow the abrasive slurry 150 to flow through the elongated sections 261 and to be cooled by a cooling agent 262. In some embodiments, a pump 270 is used to induce a flow of the slurry 150. In some embodiments, the counterflow reactor system 30 comprises an agitation device 390. The agitation device 390 according to the present invention may for this purpose be a milling device, a propeller, turbines, paddle mixers, a pump, or a transducer.

In some embodiments, the temperature of the counterflow reactor 100 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 100 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 100 comprises a fluid outlet 180.

Figure 4 is a schematic drawing of a counterflow reactor 400 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 400 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 400, a slurry outlet 130 at a second side 110 of the counterflow reactor 400, opposite the first side 105, and a fluid inlet 445. The counterflow reactor 400 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In one embodiment, the fluid inlet is a nozzle 445 positioned at the first side 105 of the counterflow reactor 400, and the method comprises introducing the fluid 150 through the nozzle 445 in a downward direction (as indicated by the arrows in Figure 4) and allowing at least a part of the fluid 150 to flow back in an upward direction, i.e. the counterflow direction with respect to the flow of the abrasive slurry 150.

This may increase the duration that the fluid 155 spend in contact with the abrasive slurry 150. Additionally, since the fluid 155 is allowed to react with the abrasive slurry 150 the part of the fluid 155 which is allowed to flow in an upward direction is smaller than the part introduced in the downward direction resulting in a net downward force acting on the abrasive slurry 150. The net downward force promotes the flow of the abrasive slurry 150 and reduces the input energy required for flowing the abrasive slurry 150.

In Figure 4 one nozzle is drawn, but in another embodiment of the present invention a reactor may comprise a plurality of nozzles.

In some embodiments, the temperature of the counterflow reactor 400 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 400 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 400 comprises a fluid outlet 180.

Figure 5 is a schematic drawing of a counterflow reactor 500 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 500 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 500, a slurry outlet 130 at a second side 110 of the counterflow reactor 500, opposite the first side 105, and a fluid inlet 140. The counterflow reactor 500 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the counterflow reactor system further comprises a fluid outlet 180 positioned at the first side 105 of the counterflow reactor 500, wherein the slurry inlet 120 is distanced from the fluid outlet 180 in a direction towards the second side 110 of the counterflow reactor 500, wherein the fluid outlet 180 is in fluid connection with the fluid inlet 140 of the counterflow reactor 500.

This allows excess fluid to be reused and increase the yield. In some embodiments, at least some of the fluid 155 is extracted from the counterflow reactor 500 through the fluid outlet 180 and introduced to a compressor 585 configured to increase the pressure of the fluid to inject it through the fluid inlet 140.

In Figures 5 and 17, the slurry inlet 120 is arranged above a slurry level 151 in the counterflow reactor 500. The slurry inlet may, however, alternatively be arranged below, or equal to, the slurry level as described generally above. In the embodiments of the other figures, the slurry

inlet 120 is generally drawn below the slurry level 151. In any of these embodiments, however, the slurry inlet may, however, alternatively be arranged above, or equal to, the slurry level as described generally above.

In some embodiments, the temperature of the counterflow reactor 500 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 500 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

Figure 6 is a schematic drawing of a counterflow reactor 600 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 600 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 600, a slurry outlet 130 at a second side 110 of the counterflow reactor 600, opposite the first side 105, and a fluid inlet 641. The counterflow reactor 600 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the counterflow reactor 600 comprises a plurality of fluid inlets 641, the method comprises introducing the fluid 150 into the counterflow reactor 600 through each fluid inlet 641 of the plurality of fluid inlets 641.

This further facilitate that the particles of the abrasive slurry 150 gets exposed to the fluid 155, dissolution of the fluid 155 in the abrasive slurry 150, keeping solids in suspension and reduce the settling inside the counterflow reactor 600. Additionally, it confines the volume comprising the fluid 155 since the flow of the fluid 155 can be further controlled, resulting in better overall control of the volume comprising the fluid 155.

In some embodiments, the fluid inlets 641 are arranged at different distances between the first side 105 and the second side 110 of the counterflow reactor 600.

In some embodiments, the fluid inlets arranged at different distances between the first side 105 and the second side 110 of the counterflow reactor 600 are fluid inlets as depicted in Figures 1-3, 5, 7, 8, 10 and 11.

The fluid inlets 641 arranged at different distances creates a more stable fluid content in the reactor over the whole volume. This further facilitate that the particles of the abrasive slurry 150 get exposed to the fluid 155, dissolution of the fluid 155 in the abrasive slurry 150, keeping solids in suspension and reduce the settling inside the counterflow reactor 600. Additionally, it

confines the volume comprising the fluid 155 since the flow of the fluid 155 can be further distributed, resulting in better overall control of the volume comprising the fluid 155.

In some embodiments, the temperature of the counterflow reactor 600 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 600 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 600 comprises a fluid outlet 180.

Figure 7 is a schematic drawing of a counterflow reactor 700 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 700 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 700, a slurry outlet 130 at a second side 110 of the counterflow reactor 700, opposite the first side 105, and a fluid inlet 140. The counterflow reactor 700 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the first cross-sectional area 161 is larger than the third cross-sectional area 163, wherein the counterflow reactor comprises a first widened section 171 having the first cross-sectional area, the first widened section 171 extending partially along the counterflow reactor 700 from the first longitudinal end 106 towards the second longitudinal end 111.

A larger first cross-sectional area 161 than the third cross-sectional area 163 helps to counter erosion of the reactor.

In some embodiments, the temperature of the counterflow reactor 700 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 700 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 700 comprises a fluid outlet 180.

Figure 8 is a schematic drawing of a counterflow reactor 800 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 800 includes a slurry

inlet 120 at a first side 105 of the counterflow reactor 800, a slurry outlet 130 at a second side 110 of the counterflow reactor 800, opposite the first side 105, and a fluid inlet 140. The counterflow reactor 800 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the counterflow reactor 800 comprises fluid inlets 842 arranged through the vertical walls of the counterflow reactor 800. This reduces the wear of the counterflow reactor.

In some embodiments, the temperature of the counterflow reactor 800 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 800 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 800 comprises a fluid outlet 180.

Figure 9 is a schematic drawing of a counterflow reactor 900 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 900 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 900, a slurry outlet 931 at a second side 110 of the counterflow reactor 900, opposite the first side 105, and a fluid inlet 943. The counterflow reactor 900 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the counterflow reactor 900 comprises a slanted bottom 999. In some embodiments the slanted bottom comprises a membrane or mesh, with a plurality of openings forming the fluid inlets 943. This prevents settling of solids in the counterflow reactor 900. This further improves the distribution of fluid over the cross-sectional area of the counterflow reactor, resulting in better overall control of the volume comprising the fluid. In some embodiments, the plurality of openings are 0.5 mm in diameter, although a skilled person recognize that openings with other diameters may be applied within the scope of the present invention.

In some embodiments, the temperature of the counterflow reactor 900 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 900 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 900 comprises a fluid outlet 180.

Figure 10 is a schematic drawing of a counterflow reactor system 90 comprising a counterflow reactor 100 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 100 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 100, a slurry outlet 130 at a second side 110 of the counterflow reactor 100, opposite the first side 105, and a fluid inlet 140. The counterflow reactor system according to the present disclosure comprises a counterflow reactor 100 configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the counterflow reactor system 90 further comprises a fluid outlet 180 positioned at the first side 105 of the counterflow reactor 100, wherein the slurry inlet 120 is distanced from the fluid outlet 180 in a direction towards the second side 110 of the counterflow reactor 100, wherein the fluid outlet 180 is in fluid connection with the fluid inlet 140 of the counterflow reactor 100.

This allows excess fluid to be reused and increase the yield. In some embodiments, at least some of the fluid 155 is extracted from the counterflow reactor 100 through the fluid outlet 180 and introduced to a compressor 585 configured to increase the pressure of the fluid to inject it through the fluid inlet 140.

In some embodiments, the counterflow reactor system 90 further comprises a heat exchanger 260 configured to cool the abrasive slurry 150. The heat exchanger 260 is external to the counterflow reactor 100. Furthermore, in some embodiments the heat exchanger comprises elongated sections 261. In some embodiments, a pump 270 is used to induce a flow of the slurry 150. Furthermore, in some embodiments the heat exchanger 260 comprises elongated sections 261 arranged generally vertically when the heat exchanger 260 is in use, and arranged to allow the abrasive slurry 150 to flow through the elongated sections 261 and to be cooled by a cooling agent 262. In some embodiments, the counterflow reactor system comprises an agitation device 390. The agitation device 390 according to the present invention may for this purpose be a milling device, a propeller, turbines, paddle mixers, a pump, or a transducer.

In some embodiments, the temperature of the counterflow reactor 100 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 100 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 100 comprises a fluid outlet 180.

Figure 11 is a schematic drawing of a counterflow reactor 1100 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 1100 includes a slurry inlet 120 at a first side 105 of the counterflow reactor 1100, a slurry outlet 130 at a second side 110 of the counterflow reactor 1100, opposite the first side 105, and a fluid inlet 140. The counterflow reactor 1100 is configured to allow an abrasive slurry 150 to react with a fluid 155.

In some embodiments, the counterflow reactor 1100 comprises one or more agitation devices 1195 configured to agitate the fluid 155 in the counterflow reactor 1100. The agitation device 1195 may be configured to agitate the fluid 155 in the counterflow reactor may for this purpose use ultrasound, the ultrasound may be induced by the use of a transducer.

In some embodiments, the temperature of the counterflow reactor 1100 lies in the range of 100 °C and 250 °C. In some embodiments, the pressure of the counterflow reactor 1100 is between 50 and 130 bar.

These conditions increase the yield of the reaction. For some fluids 155 these are relevant conditions to be a supercritical fluid, such as supercritical carbon dioxide.

In some embodiments, the reaction between the fluid 155 and the abrasive slurry 150 is exothermic.

In some embodiments, the counterflow reactor 1100 comprises a fluid outlet 180.

Figure 12 is a schematic drawing of a counterflow reactor 1200 according to some embodiments of the present disclosure. In some embodiments, the second cross-sectional area 162 is larger than the third cross-sectional area 163, wherein the counterflow reactor comprises a second widened section 172 having the second cross-sectional area 162, the second widened section 172 extending partially along the counterflow reactor 1200 from the second longitudinal 111 end towards the first longitudinal end 106.

A second cross-sectional area 162 larger than the third cross-sectional area 163 helps to counter erosion of the reactor.

Figure 13 is a schematic drawing of a counterflow reactor 1300 according to some embodiments of the present disclosure. In some embodiments, the counterflow reactor 1300 comprises the first widened section 171 and the second widened section 172, wherein the counterflow reactor 1300 comprises a neck 173 having the third cross-sectional area 163.

A larger first cross-sectional area 161 than the third cross-sectional area 163 helps to counter erosion of the reactor

A second cross-sectional area 162 larger than the third cross-sectional area 163 helps to counter erosion of the reactor.

Figure 14 is a schematic drawing of a counterflow reactor 1300 according to some embodiments of the present disclosure. In some embodiments, the slurry outlet 130 is a first slurry outlet 130, and the counterflow reactor 100 comprises a second slurry outlet 132 arranged to output slurry 150 from the counterflow reactor 1300. Alternatively, the second slurry outlet 132 may be positioned elsewhere, such as between the first slurry outlet 130 and the pump 270.

For any position of the second slurry outlet 132, a first flow of slurry may be outlet through the first slurry outlet 130 and a second flow of slurry may be outlet through the second slurry outlet 132. The second flow of slurry is smaller than the first flow of slurry. The second flow of slurry may, for example, be in the range between 0.1-2.2% of the first flow of slurry. For example the second flow of slurry may be 0.6 or 0.7% of the first flow of slurry. The second slurry outlet 132 in the configuration of Fig. 14 is arranged on the counterflow reactor 1300.

Figure 15 is a schematic drawing of a counterflow reactor system 40 according to some embodiments of the present disclosure. In some embodiments, the slurry inlet 120 is a first slurry inlet 120 and the counterflow reactor system 40 comprises a second slurry inlet 122 for providing unreacted abrasive slurry to the counterflow reactor system 40. The flow of unreacted abrasive slurry provided to the second slurry inlet 122 during steady state operation of the reactor system may be equal the second flow of slurry, such that a slurry level within the reactor 1300 is constant, allowing for some variation, such as 10% higher or 10% lower. During start up, the second flow of slurry will generally have a lower magnitude than during steady state operation, for example in order to fill up the reactor, if needed, or to allow the reaction to achieve a sufficient reaction rate.

In the configuration of Fig. 15, the second slurry inlet 122 for providing unreacted abrasive slurry to the counterflow reactor system 40 is placed in fluid communication with the first slurry inlet 120, and the second slurry inlet 122 is positioned between the heat exchanger 260 and the counterflow reactor 1300. In this way the unreacted slurry cools the slurry coming from the heat exchanger 260 further.

The second slurry inlet 122 may be positioned at alternative locations in the system. One alternative, as drawn in Figure 16, is that the second slurry inlet 122 for providing unreacted abrasive slurry to the counterflow reactor system is positioned between the first slurry outlet

130 and the pump 270. In this way, the colder unreacted slurry cools the slurry flowing from the reactor 150 before it enters the pump 270 and heat exchanger 260. In the configuration of Figure 16, the unreacted abrasive slurry flowing through the second slurry inlet 122 can have a lower pressure than in the configuration of Figure 15, thus reducing the required maximum pressure of the pump (not shown) for pumping the unreacted abrasive slurry towards the second slurry inlet 122.

In some embodiments, as for example shown in Figure 17, a slurry flow path 125 extends into the counterflow reactor 200, and ends at a first slurry inlet 121 within the counterflow reactor 200. The flow path 125 may be formed by one or more pipes, and optionally flanges (not shown) on the reactor to allow passing into the reactor. In some embodiments, a splash surface, here comprised in splash plate 123, is mounted at the end of the flow path 125 at an angle relative to the flow path 125 such that at least a part, preferably all, of the abrasive slurry 150 is directed to flow out of the first slurry inlet 121 in a direction towards the second side 110 of the counterflow reactor 200.

The splash plate may optionally be replaceable so that fewer components of the counterflow reactor system need to be replaced during maintenance.

In some embodiments, the splash plate comprises a slurry receiving surface made of an abrasion resistant material, wherein the abrasion resistant material is selected from the group consisting of hardened steels (such as AR400 or AR500), stainless steel (such as duplex, 301, 201, 431, NITRONIC 30, or NITRONIC 60 stainless steel), ceramics (such as alumina, silicon nitride, sialon, silicon carbide, boron carbide, or zirconia), and metal carbides (such as tungsten carbide or titanium carbide).

In Figure 17, the flow path 125 enters the reactor at a lateral side thereof. The flow path may alternatively enter the reactor at any other location thereof, such as at the longitudinal end 106, or even anywhere at the second side 110 of the reactor. The slurry inlet 121 is positioned in the first side 105 of the reactor, preferably above the slurry level 151, equal to the slurry level 151, or slightly below the slurry level 151, slightly meaning, for example, at most 50 cm, or at most 20 cm.

Although the present disclosure has been described with reference to specific embodiments, also shown in the appended drawings, it will be apparent to those skilled in the art that many variations and modifications may be done within the scope of the present disclosure as described in the specification and defined with reference to the claims below.

For instance, it is apparent to those skilled in the art that features found in a specific embodiment referred to in Figure 1-15 may be used in combination with and/or replace features found in another specific embodiment referred to in Figure 1-15.

CLAIMS

1. Method in a counterflow reactor system for allowing an abrasive slurry to react with a fluid, the counterflow reactor system comprising a counterflow reactor comprising a slurry inlet at a first side of the counterflow reactor, a slurry outlet at a second side of the counterflow reactor, opposite the first side, and a fluid inlet, the method comprising the steps of:
i) introducing an abrasive slurry into the counterflow reactor through the slurry inlet;
ii) introducing a fluid into the counterflow reactor through the fluid inlet;
iii) allowing the abrasive slurry to flow through the counterflow reactor from the slurry inlet towards the slurry outlet; and
iv) allowing at least a part of the introduced fluid to counterflow with respect to the flow of the abrasive slurry, and to react with the abrasive slurry.

2. Method according to claim 1, wherein the fluid inlet is arranged at the second side of the counterflow reactor.

3. Method according to claim 1 or 2, wherein
the fluid is a gas or a supercritical fluid; and/or
the gas or supercritical fluid is carbon dioxide.

4. Method according to claim 1, 2, or 3, wherein the abrasive slurry comprises particles having a particle size of at most 100 μm.

5. Method according to any one of claims 1-4, wherein the abrasive slurry comprises silicates and/or carbonates.

6. Method according to claim 5, wherein the abrasive slurry comprises olivine, wollastonite, serpentine and/or steel slag.

7. Method according to any one of claims 1-6, wherein the abrasive slurry comprises water.

8. Method according to any one of claims 1-7, wherein the temperature of the counterflow reactor lies in the range of 100 °C and 250 °C.

9. Method according to any one of claims 1-8, wherein the pressure of the counterflow reactor is between 50 and 130 bar.

10. Method according to any one of claims 1-9, wherein the reaction between fluid and the abrasive slurry is exothermic.

11. Method according to claim 10, comprising the step of:
allowing at least a part of the abrasive slurry to flow from the slurry outlet of the counterflow reactor to a heat exchanger configured to cool the abrasive slurry, and allowing the abrasive slurry to flow from the heat exchanger into the counterflow reactor through the slurry inlet, wherein the heat exchanger is arranged external to the counterflow reactor.

12. Method according to claim 11, wherein the heat exchanger comprises one or more elongated sections wherein the elongated sections are arranged generally vertical and wherein the elongated sections are cooled by a cooling agent, wherein the method comprises the step of:
allowing the slurry to flow through the elongated sections.

13. Method according to anyone of claims 1 to 12, comprising the step of:
agitating at least a part of the abrasive slurry flowing from the slurry outlet of the counterflow reactor using an agitation device and allowing the agitated abrasive slurry to flow towards the slurry inlet.

14. Method according to any one of claims 1-13, wherein the slurry is allowed to flow in a downward direction, and the fluid is allowed to flow in an upward direction inside the counterflow reactor.

15. Method according to any one of claims 1-14, wherein the fluid inlet is a nozzle positioned at the first side of the counterflow reactor, and the method comprises:
introducing the fluid through the fluid inlet in a downward direction and allowing at least a part of the fluid to flow in an upward direction.

16. Method according to any one of claims 1-15, wherein the counterflow reactor further comprises a fluid outlet positioned at the first side of the counterflow reactor, wherein the slurry inlet is distanced from the fluid outlet in a direction towards the second side of the counterflow reactor, the method comprising allowing unreacted fluid to flow out

of the counterflow reactor through the fluid outlet, and reintroducing at least a part of the fluid flowing out of the fluid outlet to the counterflow reactor via the fluid inlet.

17. Method according to any one of claims 1-16, wherein the counterflow reactor comprises a plurality of fluid inlets, the method comprising:
introducing a fluid into the counterflow reactor through each fluid inlet of the plurality of fluid inlets.

18. Method according to claim 17, wherein at least two fluid inlets are arranged at different distances between the first side and the second side of the counterflow reactor.

19. Method according to any one of claims 1-18, wherein the abrasive slurry comprises silicates and/or carbonates and water, and wherein the fluid comprises carbon dioxide, and wherein the input mass ratio of the flow of the silicates and/or carbonates is between 15 – 35 wt%, the input mass ratio of the flow of the water is between 40 – 75 wt%, the input mass ratio of the flow of the carbon dioxide is between 10 – 25 wt%, where the input mass ratios are denoted with respect to the sum of input silicates and/or carbonates, water and carbon dioxide to the counterflow reactor, optionally wherein the abrasive slurry comprises 0-10 wt% additives.

20. Method according to any one of claims 1-19, wherein the counterflow reactor extends longitudinally along a central axis, and comprises a first longitudinal end at the first side and a second longitudinal end at the second side.

21. Method according to claim 20, wherein the counterflow reactor comprises a first cross-sectional area at the first side, a second cross-sectional area at the second side, and a third cross-sectional area between the first longitudinal end and the second longitudinal end, wherein the first cross-sectional area, the second cross-sectional area and the third cross-sectional area each extend perpendicular to the central axis, and the first cross-sectional area is a first inner cross-sectional area of the counterflow reactor, the second cross-sectional area is a second inner cross-sectional area of the counterflow reactor, and the third cross-sectional area is a third inner cross-sectional area of the counterflow reactor.

22. Method according to claim 21, wherein the first cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a first widened

section having the first cross-sectional area, the first widened section extending partially along the counterflow reactor from the first longitudinal end towards the second longitudinal end.

23. Method according to claim 21, wherein the second cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a second widened section having the second cross-sectional area, the second widened section extending partially along the counterflow reactor from the second longitudinal end towards the first longitudinal end.

24. Method according to claim 22 and 23, comprising both the first widened section and the second widened section, wherein the counterflow reactor comprises a neck section having the third cross-sectional area.

25. Method according to claim 22, wherein the ratio between the first cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.2 and 5, more preferably between 1.3 and 2.25.

26. Method according to any one of claims 1-25, wherein the fluid is inlet is arranged through the vertical walls of the counterflow reactor.

27. Method according to any one of claims 1-26, wherein one or more agitation devices is configured to agitate the fluid in the counterflow reactor.

28. Method according to claim 23, wherein the ratio between the second cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.15 and 5, more preferably between 1.2 and 2.25.

29. Counterflow reactor system for allowing an abrasive slurry to react with a fluid, wherein the counterflow reactor system comprises a counterflow reactor comprising: a slurry inlet at a first side of the counterflow reactor, a slurry outlet at a second side of the counterflow reactor, opposite the first side, and a fluid inlet configured to introduce the fluid into the counterflow reactor and such that, when in use, at least a part of the introduced fluid flows in a direction opposite to a flow of the abrasive slurry.

30. Counterflow reactor system according to claim 29, wherein the counterflow reactor comprises a slanted bottom.

31. Counterflow reactor system according to claim 29 or 30, wherein the fluid inlet comprises a nozzle arranged to inject the fluid in a downward direction into the counterflow reactor.

32. Counterflow reactor system according to any one of claims 29-31, wherein the counterflow reactor system is adapted for pressures up to 130 bar and wherein the counterflow reactor is adapted for temperatures up to 250°C.

33. Counterflow reactor system according to any one of claims 29-32, wherein the fluid inlet is arranged at the second side of the counterflow reactor.

34. Counterflow reactor system according to claim 33, wherein the counterflow reactor further comprises a fluid outlet positioned at the first side of the counterflow reactor, wherein the slurry inlet is distanced from the fluid outlet in a direction towards the second side of the counterflow reactor, wherein the fluid outlet is in fluid connection with the fluid inlet of the counterflow reactor.

35. Counterflow reactor system according to any one of claims 29-33, comprising a plurality of fluid inlets.

36. Counterflow reactor system according to claim 35, wherein the fluid inlets of the plurality of fluid inlets are spaced from each other over a length of the counterflow reactor.

37. Counterflow reactor system according to any one of claims 29-36, comprising one or more agitation devices configured to agitate the abrasive slurry and/or the fluid.

38. Counterflow reactor system according to claim 37, wherein one of the one or more agitation devices is configured to agitate the fluid in the counterflow reactor.

39. Counterflow reactor system according to claim 37, wherein one of the one or more agitation devices is arranged external to the counterflow reactor and configured to agitate the abrasive slurry.

40. Counterflow reactor system according to any one of claims 29-39, wherein the counterflow reactor system comprises a heat exchanger, wherein the heat exchanger is external to the counterflow reactor and in fluid communication with the slurry outlet.

41. Counterflow reactor system according to claim 40, wherein the heat exchanger comprises one or more elongated sections arranged generally vertically when the heat exchanger is in use, and arranged to allow the abrasive slurry to flow through the elongated sections and to be cooled by a cooling agent.

42. Counterflow reactor system according to any one of claims 29-41, wherein the fluid inlet is arranged through the vertical walls of the reactor.

43. Counterflow reactor system according to any one of claims 29-42, wherein the counterflow reactor extends longitudinally along a central axis, and comprises a first longitudinal end at the first side and a second longitudinal end at the second side.

44. Counterflow reactor system according to claim 43, wherein the counterflow reactor comprises a first cross-sectional area at the first side, a second cross-sectional area at the second side, and a third cross-sectional area between the first side and the second side, wherein the first cross-sectional area, the second cross-sectional area and the third cross-sectional area each extend perpendicular to the central axis, and the first cross-sectional area is a first inner cross-sectional area of the counterflow reactor, the second cross-sectional area is a second inner cross-sectional area of the counterflow reactor, and the third cross-sectional area is a third inner cross-sectional area of the counterflow reactor.

45. Counterflow reactor system according to claim 43 or 44, wherein the first cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a first widened section having the first cross-sectional area, the first widened section extending partially along the counterflow reactor from the first longitudinal end towards the second longitudinal end.

46. Counterflow reactor system according to claim 44, wherein the second cross-sectional area is larger than the third cross-sectional area, wherein the counterflow reactor comprises a second widened section having the second cross-sectional area, the second widened section extending partially along the counterflow reactor from the second longitudinal end towards the first longitudinal end.

47. Counterflow reactor system according to claim 45 and 46, comprising both the first widened section and the second widened section, wherein the counterflow reactor comprises a neck section having the third cross-sectional area.

48. Counterflow reactor system according to claim 47, wherein the ratio between the first cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.2 and 5, more preferably between 1.3 and 2.25.

49. Counterflow reactor system according to claim 48, wherein the ratio between the second cross-sectional area and the third cross-sectional area is between 1.1 and 9, preferably between 1.15 and 5, more preferably between 1.2 and 2.25.