

COMPOUND STATIC MIXER REACTOR AND APPLICATIONS THEREOF**FIELD**

[0001] The present disclosure generally relates to a compound static mixer element, a compound catalytic static mixer element, and dehydrogenation and hydrogenation processes using a compound catalytic static mixer element, configured for use with continuous flow chemical reactors, for example tubular continuous flow chemical reactors for heterogeneous catalysis reactions.

BACKGROUND

[0002] Continuous flow chemical reactors generally comprise a tubular reaction chamber with reactant fluids being continuously fed into the reaction chamber to undergo a chemical reaction to continuously form products which flow out from the reaction chamber.

[0003] Continuous flow reactors used in catalytic reactions typically employ packed bed reaction chambers in which the reaction chamber is packed with solid catalyst particles that provide catalytic surfaces on which the chemical reaction can occur. Static mixers are used for pre-mixing of fluid streams prior to contact with the packed bed reaction chambers and downstream of these chambers to transfer heat between the central and the outer regions of the reactor tubes. The static mixers comprise solid structures that interrupt the fluid flow to promote mixing of the reactants prior to reaction in the packed bed reaction chambers and for promoting desirable patterns of heat transfer downstream of these chambers. Static mixers are also used independent of packed beds since some reactants do not require a catalyst to activate their reaction.

[0004] Static mixers have traditionally been directed to mixing fluidic components, when used with chemical reactors. In most chemical reactors several static mixers would be arranged in series as inserts within tubing which can extend to several meters to provide efficient mixing systems. Towards improving process productivity through increased reaction yields, there is a clear need for developing enhanced static mixers and catalytic static mixers for continuous flow chemical reactors that are readily removable and easily replaced, allow further re-design enhancement and are capable of

providing more efficient mixing, heat transfer and catalytic reaction of reactant chemical and/or electrochemical reactants. As described further below, static mixers can be designed as inserts for use with in-line continuous flow reactor systems and can be coated with catalysts to provide heterogeneous catalysis for on-demand hydrogen production. Further details and embodiments of the compound static mixer inserts are described below.

[0005] Hydrogen is an ideal fuel for clean energy, replacing traditional petroleum based feedstocks. Two significant challenges of using hydrogen include efficient hydrogen production and safe hydrogen storage. While there are many technologies focussed on developing efficient catalysts or methods of conversion, industrial scale production systems remains an emerging market. Once hydrogen is produced, compression and liquefaction technologies have been used to store hydrogen. These introduce safety concerns and low storage density, as well as transportation, boil-off losses, and other high-cost problems.

[0006] Hydrogen carriers represent an attractive alternative to store hydrogen in chemical bonds and can be used to release hydrogen as required. However, the production of hydrogen from a hydrogen carrier is a catalytic process and there remains a need to develop efficient systems that can address on demand conversion to hydrogen while maintaining efficient flow of reactants to separate gaseous hydrogen produced during the process.

SUMMARY

[0007] In one aspect there is provided a compound static mixer element comprising: at least a first fluidic chamber comprising a plurality of axially spaced flow directing panels each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define a plurality of separate flow channels, wherein each flow channel extends along the longitudinal axis of the first fluidic chamber and is configured at or near one opposing end for fluidic connection with an adjacent flow channel such that, in use, one or more fluidic reactants entering the first fluidic chamber into a first flow channel flow in a serpentine direction through the plurality of adjacent separate flow channels such that the one or

more fluidic reactants flow through each separate flow channel consecutively, and wherein each flow channel comprises a patterned porous scaffold defining a plurality of passages configured for mixing one or more fluidic reactants during flow and reaction thereof through the patterned porous scaffold such that the patterned porous scaffold links the plurality of flow directing panels.

[0008] In another aspect there is provided a continuous flow chemical reactor for use in reaction of one or more fluidic reactants, the reactor comprising: the compound static mixer element as described by any one or more embodiments herein; a reactor chamber configured for receiving and housing the compound static mixer element; at least one reactant inlet for supply of the one or more fluidic reactants to the reactor chamber section; and at least one outlet in fluidic communication with the static mixer for receiving an output stream comprising a product of the reaction, wherein the inlet and outlet is separated by the static mixer element, and wherein the static mixer element disposed within the reactor chamber is configured for dispersing and mixing the one or more fluidic reactants during flow and reaction thereof through the mixer.

[0009] In another aspect there is provided a system for providing a continuous flow chemical reaction comprising: a continuous flow chemical reactor comprising a compound static mixer as described by any one or more embodiments herein or a continuous flow chemical reactor as described by any one or more embodiments herein; a pump for providing fluidic flow for one or more fluidic reactants and any products thereof through the reactor; one or more heat exchangers to allow for control of the temperature of the reactor, reactor chamber section, static mixer element, or fluidic components thereof; and a controller for controlling one or more of the parameters of the system selected from concentration, flow rate, temperature, pressure, and residence time, of the one or more fluidic reactants, or sources or products thereof.

[0010] In one aspect there is provided a process for releasing hydrogen from a hydrogen carrier comprising (i) introducing the hydrogen carrier into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments herein; (ii) dehydrogenating the hydrogen carrier as it passes through the reactor whereby said dehydrogenating produces hydrogen and a dehydrogenated carrier; (iii)(a) obtaining an output stream comprising hydrogen and

the dehydrogenated carrier; and (iv) separating hydrogen and the dehydrogenated carrier.

[0011] In another aspect there is provided a process for synthesizing a product by hydrogenation reaction of at least a first fluidic reactant with a second fluidic reactant, the process comprising: (i) introducing at least a first and second fluidic reactant, or source thereof, into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments herein via the one or more reactant inlets; (ii) operating the reactor, or control means thereof, to provide flow and hydrogenation reaction of the first and second fluidic reactant through the compound static mixer; and (iii) obtaining an output stream comprising a product of a hydrogenation reaction of at least the first and second fluidic reactants.

[0012] In another aspect there is provided a continuous flow chemical reactor for use in dehydrogenation and/or hydrogenation reactions, the reactor comprising: a compound catalytic static mixer element as described by any one or more embodiments herein; a reactor chamber configured for receiving and housing the compound catalytic static mixer element; at least one reactant inlet for supply of one or more fluidic reactants to the reactor chamber section; and at least one outlet in fluidic communication with the static mixer for receiving an output stream comprising a product of the reaction, wherein the inlet and outlet is separated by the static mixer element, and wherein the compound catalytic static mixer element disposed within the reactor chamber is configured for dispersing and mixing the one or more fluidic reactants during flow and reaction thereof through the mixer. In some embodiments, the continuous flow chemical reactor according to any one or more embodiments or examples described herein for producing hydrogen. The continuous flow chemical reactor according to any one or more embodiments or examples described herein for producing hydrogen wherein the one or more fluidic reactants may be a hydrogen carrier. In some embodiments, the hydrogen carrier may be a LOHC.

[0013] In another aspect there is provided a system for providing a continuous flow chemical reaction for use in dehydrogenation and/or hydrogenation reactions, the system comprising: the continuous flow chemical reactor according to any one or more embodiments described herein; a pump for providing fluidic flow for one or more

fluidic reactants and any products thereof through the reactor; one or more heat exchangers to allow for control of the temperature of the reactor, reactor chamber section, static mixer element, or fluidic components thereof; and a controller for controlling one or more of the parameters of the system selected from concentration, flow rate, temperature, pressure, and residence time, of the one or more fluidic reactants, or sources or products thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Preferred embodiments of the present disclosure will now be further described and illustrated, by way of example only, with reference to the accompanying drawings in which:

[0015] **Figure 1a** is a series of schematic depictions of a compound static mixer element and flow path of reactants and reaction products thereof, as described by any one of more embodiments herein.

[0016] **Figure 1b** is a schematic depiction of a compound static mixer element and flow path of reactants and reaction products thereof, as described by any one of more embodiments herein.

[0017] **Figure 1c** is a schematic 2D representation of a classic serpentine motion.

[0018] **Figure 1d** is a schematic 2D representation of a rotated serpentine motion.

[0019] **Figure 2** is a schematic of a continuous flow reactor, as described by any one of more embodiments herein.

[0020] **Figure 3** is a 3D image of the continuous flow reactor system, as described by any one of more embodiments herein.

[0021] **Figure 4a** is an image showing tracer transport in laminar and turbulent flows, as described by any one of more embodiments herein.

[0022] **Figure 4b** is a series of images showing different flow paths having a serpentine motion where 4b(iA) shows the fluidic flow path about an axis parallel to the overall direction of flow in a cylindrical pattern where the inlet and outlet are at opposing ends of the compound static mixer; 4b(iB) shows the fluidic flow path about

an axis parallel to the overall direction of flow in a cylindrical pattern where the inlet and outlet are on the same side of the compound static mixer; and 4b(ii) is a prior art mixer showing a fluidic flow path in a serpentine motion about an axis perpendicular to the direction of flow. Figure 4b(iA) and (iB) are examples of a rotated serpentine motion, while Figure 4b(ii) can be described as a classic serpentine motion.

[0023] **Figure 5** shows a compound static mixer coated with catalyst and showing plurality of flow channels and flow directing panels therebetween, as described by any one of more embodiments herein.

[0024] **Figure 6** shows a compound static mixer coated with catalyst (left) and compound static mixer packed into the reactor tube (right), as described by any one of more embodiments herein.

[0025] **Figure 7** shows a schematic of continuous flow reactor system, as described by any one of more embodiments herein.

[0026] **Figure 8** shows a series of graphs A): reaction conversions (%) for the MCH/Toluene system as a function of run time over a range of process temperatures (TC0) at fixed process pressure, $p = 5$ bar and MCH feed rate of 1.4 ml.min^{-1} ; and B) conversion % under steady state as a function of process temperature (TC0).

[0027] **Figure 9** shows a series of graphs A): reaction conversions (%) for the MCH/Toluene system for different MCH feed rates (Q) at fixed process temperature, $TC0 = 330^\circ\text{C}$ and pressure, $p = 5$ bar; and B) conversion % under steady state as a function of MCH liquid hourly space velocity (LHSV).

DETAILED DESCRIPTION

[0028] The present disclosure describes the following various non-limiting embodiments, which relate to investigations undertaken to identify compound static mixer elements capable of being inserted into a hollow tubular portion of a reactor and readily removable and easily replaced, providing efficient heat transfer for use with continuous flow chemical reactors. It was surprisingly found that incorporating catalytic material on the surface of additive manufactured compound static mixers can provide efficient catalytic reaction of reactants in continuous flow chemical reactors,

mixing, and heat transfer. The word compound is intended to communicate two or more elements that together form a static mixer or static mixer element that operates as a single unit for a purpose, akin to a compound eye. The continuous flow chemical reactors comprising the compound static mixers developed using additive manufacturing can also be operated at commercially relevant flow rates, and may also provide such operation with manageable back pressures (an indicator of the resistance to flow) as described in further detail below. According to at least some embodiments described herein, the compound static mixers can advantageously be configured and used with in line continuous flow reactors as inserts with the compound static mixer as an integral part of the reactor tube itself. Further advantages of the compound static mixers, at least according to some embodiments as disclosed herein, is that they can be configured and used with multiple pass in-line continuous flow reactors. The compound static mixers may be tubular and used with tubular continuous flow chemical reactors. Additionally, that the patterned porous scaffold of the compound static mixer element can be coated with catalytic material to provide a compound catalytic static mixer element for use in a reaction requiring catalysis.

[0029] Static mixers have traditionally been directed to mixing fluidic components, and when used with chemical reactors, as pre-mixing elements prior to reactions using packed bed systems. As mentioned, chemical reactors typically use packed bed systems and therefore are not directed to higher flow rate operations in which the present compound static mixers can operate.

[0030] Compared to current heterogeneous catalysis systems, such as packed beds, the present compound static mixers have been shown to provide various advantages. Additive manufacturing technology (i.e. 3D printing) enables flexibility in design and configuration of the compound static mixers, can be catalytically coated to provide continuous catalysis reactions within a chemical reactor, provide efficient control of mixing and flow conditions inside the continuous flow reactor, and enhanced heat and mass transfer characteristics and reduced back pressures compared to packed bed systems. In addition, various coating techniques have been found to be surprisingly suitable for catalytically coating the compound static mixers and were suitable for application with a wide variety of metal catalysts. It has been surprisingly found that

compared to existing static mixers or catalytic static mixers of the same length, compound static mixers and compound catalytic static mixers offer a further advantage where fluidic reactants entering a first fluidic chamber flow in a serpentine direction through the plurality of separate flow channels. This means a single compound static mixer element or a compound catalytic static mixer element can replace at least two or more static mixers or catalytic static mixers required in a flow reactor allowing the industrial production and use of a compact flow reactor. The term compact is used to denote the length of the tubing within a reactor where for example, when several static mixers are used as separate inserts in a lengthy tube within a reactor, the same effect can be replicated using a single compound static mixer which fits into the same length of tubing as a single static mixer. Therefore, one or more advantages of the present disclosure may be provided by the compound static mixer having a fluidic flow path in a serpentine configuration, including cost reduction of manufacture, capacity increase, and compactness of the mixer. According to further embodiments, one or more advantages of the compound static mixer, as described herein, may also include continuous removal of hydrogen.

[0031] As described further below, the static mixers can be configured as elements to provide inserts for use with in-line continuous flow reactor systems. The compound static mixers can also provide heterogeneous catalysis, including dehydrogenation and hydrogenation, which is of significant importance to on-demand hydrogen production, and to chemical manufacturing, and is broad ranging including the production of fine and specialty chemicals, pharmaceuticals, food and agrochemicals, consumer products, and petrochemicals. Further details and embodiments of the compound static mixer inserts are described below.

Definitions

General Definitions and Terms

[0032] In the following description, reference is made to the accompanying drawings which form a part hereof, and which is shown, by way of illustration, several embodiments. It is understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present disclosure.

[0033] With regards to the definitions provided herein, unless stated otherwise, or implicit from context, the defined terms and phrases include the provided meanings. Unless explicitly stated otherwise, or apparent from context, the terms and phrases below do not exclude the meaning that the term or phrase has acquired by a person skilled in the relevant art. The definitions are provided to aid in describing particular embodiments, and are not intended to limit the claimed invention, because the scope of the invention is limited only by the claims. Furthermore, unless otherwise required by context, singular terms shall include pluralities and plural terms shall include the singular.

[0034] All publications discussed and/or referenced herein are incorporated herein in their entirety.

[0035] Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is solely for the purpose of providing a context for the present disclosure. It is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present disclosure as it existed before the priority date of each claim of this application.

[0036] Throughout this disclosure, unless specifically stated otherwise or the context requires otherwise, reference to a single step, composition of matter, group of steps or group of compositions of matter shall be taken to encompass one and a plurality (i.e., one or more) of those steps, compositions of matter, groups of steps or groups of compositions of matter. Thus, as used herein, the singular forms “a”, “an” and “the” include plural aspects unless the context clearly dictates otherwise. For example, reference to “a” includes a single as well as two or more; reference to “an” includes a single as well as two or more; reference to “the” includes a single as well as two or more and so forth.

[0037] Those skilled in the art will appreciate that the disclosure herein is susceptible to variations and modifications other than those specifically described. It is to be understood that the disclosure includes all such variations and modifications. The disclosure also includes all of the examples, steps, features, methods, compositions,

coatings, processes, and coated substrates, referred to or indicated in this specification, individually or collectively, and any and all combinations or any two or more of said steps or features.

[0038] The term “and/or”, e.g., “X and/or Y” shall be understood to mean either “X and Y” or “X or Y” and shall be taken to provide explicit support for both meanings or for either meaning.

[0039] Unless otherwise indicated, the terms “first,” “second,” etc. are used herein merely as labels, and are not intended to impose ordinal, positional, or hierarchical requirements on the items to which these terms refer. Moreover, reference to a “second” item does not require or preclude the existence of lower-numbered item (e.g., a “first” item) and/or a higher-numbered item (e.g., a “third” item).

[0040] As used herein, the phrase “at least one of”, when used with a list of items, means different combinations of one or more of the listed items may be used and only one of the items in the list may be needed. The item may be a particular object, thing, or category. In other words, “at least one of” means any combination of items or number of items may be used from the list, but not all of the items in the list may be required. For example, “at least one of item A, item B, and item C” may mean item A; item A and item B; item B; item A, item B, and item C; or item B and item C. In some cases, “at least one of item A, item B, and item C” may mean, for example and without limitation, two of item A, one of item B, and ten of item C; four of item B and seven of item C; or some other suitable combination.

[0041] It is to be appreciated that certain features that are, for clarity, described herein in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features that are, for brevity, described in the context of a single embodiment, may also be provided separately or in any sub-combination.

[0042] Throughout the present specification, various aspects and components of the invention can be presented in a range format. The range format is included for convenience and should not be interpreted as an inflexible limitation on the scope of the invention. Accordingly, the description of a range should be considered to have

specifically disclosed all the possible sub-ranges as well as individual numerical values within that range, unless specifically indicated. For example, description of a range such as from 1 to 5 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 5, from 3 to 5 etc., as well as individual and partial numbers within the recited range, for example, 1, 2, 3, 4, 5, 5.5 and 6, unless where integers are required or implicit from context. This applies regardless of the breadth of the disclosed range. Where specific values are required, these will be indicated in the specification.

[0043] Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

[0044] Any embodiment of the present disclosure herein shall be taken to apply *mutatis mutandis* to any other embodiment of the disclosure unless specifically stated otherwise.

Compound Static Mixer Element

[0045] In one aspect of the present disclosure there is provided a compound static mixer element comprising: at least a first fluidic chamber comprising a plurality of axially spaced flow directing panels each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define a plurality of separate flow channels, wherein each flow channel extends along the longitudinal axis of the first chamber and is configured at or near one opposing end for fluidic connection with an adjacent flow channel such that, in use, one or more fluidic reactants entering the first fluidic chamber into a first flow channel flow in a serpentine direction through the plurality of adjacent separate flow channels such that the one or more fluidic reactants flow through each separate flow channel consecutively, and wherein each flow channel comprises a patterned porous scaffold defining a plurality of passages configured for mixing one or more fluidic reactants during flow and reaction thereof through the patterned porous scaffold such that the patterned porous scaffold links the plurality of flow directing panels.

[0046] It will be appreciated that flow in a serpentine direction means that the fluidic reactants or reaction products thereof flow through one flow channel and pass into an adjacent flow channel through a fluidic connection point defined at or near one opposing end of each flow directing panel. This flow pattern continues in a serpentine direction through each flow channel that is defined by each flow directing panel of the first fluidic chamber. Two particular examples of this fluid flow pattern may be as depicted in Figures 1a and b. In other words, the fluidic reactants or reaction products flow between flow channels having an elongated flow path before it turns and flows into adjacent elongated flow channels in the opposite direction. This motion of fluid flow is referred to herein as serpentine motion or flow in a serpentine direction or serpentine pattern. The flow of the fluidic reactants or reaction products is in the same direction as the overall flow (net flow) or opposite direction (180°) to the overall flow and flows through each separate flow channel consecutively in a serpentine motion. The flow of fluidic reactants or reaction products according to at least some embodiments or examples described herein serpentine about an axis perpendicular to the overall direction of flow in a cylindrical direction. It can be understood that flow in a serpentine direction, as described herein, may be based on rotated serpentine motion (Fig. 1d), as opposed to a classic serpentine (Fig. 1c), wherein the elongated flow channels configured in the longitudinal axis are in the same direction as the overall flow.

[0047] In an embodiment, at least a portion of the one or more of the plurality of flow directing panels may be designed to direct and/or improve fluid flow between adjacent flow channels. In some embodiments, the geometry at or near opposing ends of each adjacent flow directing panels may be designed to improve fluidic communication between adjacent flow channels. In some embodiments, each flow channel is in fluid communication with an adjacent flow channel via an indent in each flow directing panel, wherein the indent may be at or near opposing ends of each adjacent flow directing panel to allow the one or more fluidic reactants to pass through each flow channel in a serpentine direction. In some embodiments, the flow directing panels may form one or more segmented flow directing panels along the longitudinal axis of the

first fluidic chamber. In other words, each flow directing panel can be staggered along the longitudinal axis of the first fluidic chamber whilst maintaining the fluid flow through the flow channels. It will be appreciated that the first fluidic chamber may be composed of flow directing panels extending the longitudinal axis of the first fluidic chamber, segmented flow directing panels extending the longitudinal axis of the first fluidic chamber, or a combination of both. In another embodiment the flow directing panels may be arranged in a spiral fashion such that the flow of fluid in each flow channel is directed in a helical flow direction, inducing a vortex flow within each flow channel which can lead to increased turbulence, fluid mixing, heat and mass transfer.

[0048] It will be appreciated that the patterned porous scaffold is a continuous porous matrix linking each flow directing panel within the first fluidic chamber.

[0049] In some embodiments, the end of the indent of each flow directing panel may comprise any geometry and/or be positioned at an angle. For example, the end of the indent may be slanted or designed with an irregularly shaped edge, e.g. curved. In other embodiments or examples, the end of the indent of each flow directing panel may be at a 90° angle to the general direction of fluid flow. In other embodiments or examples, the end of the indent of each flow directing panel may have an angle less than 90° to the general direction of fluid flow. In yet other embodiments or examples, the end of the indent of each flow directing panel may have an angle greater than 90° to the general direction of fluid flow. It will be appreciated that the geometry and/or angle of the end of the indent of each flow directing panel can assist in changing the fluid momentum thereby aiding in directing the fluid through the fluidic connection point to each subsequent flow channel.

[0050] The compound static mixer element may comprise a plurality of axially spaced flow directing panels which act as separating walls such that each axially spaced wall defines the plurality of flow channels. In some embodiments, the plurality of flow directing panels may be spaced apart thereby creating a plurality of flow channels with approximately the same cross section area. This may be advantageous for some reactions as it could provide approximately equal flow rates within each of the plurality of flow channels. In another embodiment, the plurality of flow directing panels may be spaced non-uniformly thereby creating a plurality of flow channel with different cross-

sectional areas. For example, the radial spacing of flow directing panels defining flow channels approaching the outlet may be larger or smaller, relative to the spacing of those flow directing panels at defining flow channels closer to the inlet, thereby increasing or decreasing the cross sectional area of flow channels closer to the outlet. This may provide uniform residence times in flow channels closer to the outlet. In some instances, this may be advantageous as reaction rates may decrease with decreasing reactant concentration(s) and greater residence times in flow channels closer to the outlet may provide for a more uniform amount of the catalytic reaction to occur in each flow channel and/or a more uniform distribution of heat generated or consumed due to the reaction in each flow channel.

[0051] In some embodiments, the number of axially spaced flow directing panels may be greater than 2, 3, 4, 5, 6, 7, 8, 9, or 10 defining greater than 2, 3, 4, 5, 6, 7, 8, 9, or 10 separate flow channels respectively. In some embodiments, the number of axially spaced flow directing panels is less than 10, 9, 8, 7, 6, or 5 defining less than 10, 9, 8, 7, 6, or 5 separate flow channels respectively. The number of axially spaced flow directing panels may be in a range provided by any two or more of the upper and/or lower amounts, for example the number of axially spaced flow directing panels may be between about 2 and 10 defining between 2 and 10 flow channels, the number of axially spaced flow directing panels may be between about 4 and 8 defining between 4 and 8 flow channels, or the number of axially spaced flow directing panels may be between about 5 and 7 defining between 5 and 7 separate flow channels. In one preferred embodiment or example, the compound static mixer element may comprise 6 axially spaced flow directing panels defining 6 flow channels.

[0052] The dimensions of the compound static mixer element may be varied depending on the application. In some embodiments, the diameter (in mm) of the compound static mixer may be in the range of 15 to 5000, 20 to 2500, 25 to 1000, or 30 to 500. The diameter (in mm) of the compound static mixer may, for example, be at least about 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 250, 500, 750, 1000, 2500, or 5000. The diameter (in mm) of the compound static mixer may, for example, be about 5000, 2500, 1000, 750, 500, 250, 200, 150, 100, 95, 90, 85,

80, 75, 70, 65, 60, 55, 50, 45, 40, 35, 30, 25, 20, or 15. Combinations of these upper and lower values to form various ranges are also possible.

[0053] The geometry of the first fluidic chamber can be of any suitable geometry to allow for the plurality of axially spaced flow directing panels to define the plurality of flow channels wherein the flow pattern of the fluid flow is a serpentine direction. In some embodiment, the first fluidic chamber will be substantially tubular in shape. The dimensions of the first fluidic chamber may be varied depending on the application. In some embodiments, the diameter (in mm) of the first fluidic chamber may be in the range of about 15 to 5000, 20 to 2500, 30 to 1000, or 40 to 500. The diameter (in mm) of the first fluidic chamber may, for example, be at least about 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 250, 500, 750, 1000, 2500, or 5000. The diameter (in mm) of the first fluidic chamber may, for example, be less than about 5000, 2500, 1000, 750, 500, 250, 200, 150, 100, 75, or 50. Combinations of these upper and lower values to form various ranges are also possible.

[0054] In some embodiments, the length (in mm) of the first fluidic chamber may be in a range between 15 and 5000. The length (in mm) of the first fluidic chamber may, for example, be in the range of about 15 to 5000, 20 to 2500, 50 to 2000, or 100 to 1000. The length (in mm) of the first fluidic chamber may, for example, be at least about 10, 50, 100, 250, 500, 750, 1000, 1500, 2000, 2500, 3000, 4000, or 5000. The length (in mm) of the first fluidic chamber may, for example, be less than about 5000, 2500, 1000, 750, 500, 300, 250, 200, 150, 125, 100, 50, 20, or 15. Combinations of these upper and lower values to form various ranges are also possible.

[0055] The aspect ratios (L/d) of the first chamber may be provided in a range suitable for industrial scale flow rates for a particular reaction. The aspect ratios may, for example, be in the range of about 1 to 5000, 2 to 4000, 3 to 3000, 4 to 2000, 5 to 1000, or 5 to 500. The aspect ratios may, for example, be less than about 5000, 4500, 4000, 3500, 3000, 2500, 2000, 1500, 1000, 750, 500, 250, 200, 150, 100, 75, 50, 25, 20, 15, 10, 9, 8, 7, 6, 5, 4, 3, or 2. The aspect ratios may, for example, be greater than about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 50, 75, 100, 200, 250, 300, 350, 400, 450, 500, 750, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, or 5000. Combinations of these upper and lower values to form various ranges are also possible.

[0056] In some embodiments, the static mixer element may further comprise an inner second heat cavity chamber concentrically positioned with respect to the first fluidic chamber. In some embodiments, the diameter of the second heat cavity chamber will be less than the diameter of the first fluidic chamber. In an embodiment, the second heat cavity chamber will be substantially tubular in shape. The dimensions of the second heat cavity chamber may be varied depending on the application. In some embodiments, the diameter (in mm) of the second heat cavity chamber may be in the range of about 1 to 2500, 3 to 1000, 4 to 500, 5 to 150, or 10 to 100. The diameter (in mm) of the second heat cavity chamber may, for example, be at least about 1, 5, 10, 25, 50, 75, 100, 250, 500, or 1000. The diameter (in mm) of the second heat cavity chamber may, for example, be less than about 2500, 1000, 750, 500, 250, 200, 150, 100, 75, or 50. Combinations of these upper and lower values to form various ranges are also possible. It will be appreciated that the diameter of the second heat cavity chamber will be dependent on commercially available heating elements and can be tailored to accommodate any diameter. For example, the diameter of the second heat cavity chamber may be in a range of between about 9 mm to about 19 mm,

[0057] In some embodiments, the ratio of the first fluidic chamber to the second heat cavity chamber may be in a range between about 0.5 to about 3. The ratio of the first fluidic chamber to the second heat cavity chamber may be less than about 3, 2.5, 2, 1.5, 1 or 0.5. The ratio of the first fluidic chamber to the second heat cavity chamber may be at least about 0.5, 1, 1.5, 2, 2.5, or 3. Combinations of these upper and lower values to form various ranges are also possible.

[0058] In some embodiments, the second heat cavity chamber is configured to support a heat exchanger. In an embodiment, the second heat cavity chamber may be an inner hollow chamber configured to optionally support a heat exchanger. It will be appreciated that the heat exchanger may be of any suitable type. In some embodiments, the heat exchanger is a tubular heat exchanger. In some embodiments, the heat exchanger is a heat rod. The diameter of the heat exchanger (e.g. heat rod) may be sufficiently similar to the diameter of the second heat cavity chamber such that when inserted at least a portion of the outer surface of the heat exchanger is in contact with at least a portion of the surface defining the second heat cavity chamber. Advantageously,

this configuration allows for the fluidic reactants or reaction products thereof within the plurality of flow channels to be in thermal communication with the heat exchanger thereby providing a mechanism to remove energy generated by the chemical reaction(s). Alternatively, the thermal communication allows for energy to be introduced into system if the reaction is endothermic. Furthermore, the configuration allows for the control of the system temperature.

[0059] In one embodiment, as depicted in Figure 1a, a compound static mixer element of the present disclosure is shown having a first fluidic chamber (A) comprising a six axially spaced flow directing panels (1) each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define six separate flow channels (2). In other embodiment, as depicted in Figure 1b, the flow directing panels (1) may be segmented along the longitudinal axis of the first fluidic chamber (A). The flow channels extend along the longitudinal axis of the first fluidic chamber and are configured at or near one opposing end for fluidic connection with an adjacent flow channel (3). In use, one or more reactants entering the first fluidic chamber through an inlet (4) flow in a serpentine direction through the plurality of separate flow channels (5) and the reaction mixture exits the element through an outlet (6). Each flow channel comprises a patterned porous scaffold (7) defining a plurality of passages (8) configured for mixing one or more reactants during flow and reaction thereof through the mixer. Also depicted is a cross sectional view from the inlet (4) and outlet (6) end showing the six axially spaced flow directing panels (1) each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define six separate flow channels (2), the inlet (4), the outlet, and an inner second heat cavity chamber (B) concentrically positioned with respect to the first fluidic chamber (A). Similarly depicted is a cross section view from opposing end showing the six axially spaced flow directing panels (1) each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define three separate flow channels (2), and an inner second heat cavity chamber (B) concentrically positioned with respect to the first fluidic chamber (A).

[0060] In various embodiments, the geometry or configuration may be chosen to enhance one or more characteristics of the compound static mixer element selected from: the specific surface area, volume displacement ratio, strength and stability for high flow rates, suitability for fabrication using additive manufacturing, and to achieve one or more of: a high degree of chaotic advection, turbulent mixing, catalytic interactions, and heat transfer.

[0061] In some embodiments, the patterned porous scaffold may be configured to enhance chaotic advection or turbulent mixing, for example cross-sectional, transverse (to the net flow) or localised turbulent mixing. The geometry of the patterned scaffold may be configured to change the localised flow direction or to split the flow more than a certain number of times within a given length along a longitudinal axis of the static mixer element, such as more than 200 m^{-1} , optionally more than 400 m^{-1} , optionally more than 800 m^{-1} , optionally more than 1500 m^{-1} , optionally more than 2000 m^{-1} , optionally more than 2500 m^{-1} , optionally more than 3000 m^{-1} , optionally more than 5000 m^{-1} . The geometry or configuration of the patterned scaffold may comprise more than a certain number of flow splitting structures within a given volume of the compound static mixer, such as more than 100 m^{-3} , optionally more than 1000 m^{-3} , optionally more than $1 \times 10^4\text{ m}^{-3}$, optionally more than $1 \times 10^6\text{ m}^{-3}$, optionally more than $1 \times 10^9\text{ m}^{-3}$, optionally more than $1 \times 10^{10}\text{ m}^{-3}$.

[0062] In another embodiment, the compound static mixer element may comprise a patterned porous scaffold provided by a repetitive design of porous segments repeated periodically along the longitudinal axis of the first fluidic chamber to form a continuous lattice of interconnected segments configured for facilitating mixing of reactants and heat transfer. The geometry or configuration of the patterned porous scaffold may be substantially tubular or rectilinear. The patterned porous scaffold may comprise a repeated structure. The patterned porous scaffold may comprise a plurality of similar structures repeated periodically along the longitudinal axis of the porous scaffold. The geometry or configuration of the patterned porous scaffold may be consistent along the length of the patterned porous scaffold. The geometry of the patterned porous scaffold may vary along the length of the patterned scaffold. The passages are configured for mixing one or more fluidic reactants during flow and reaction thereof through the

mixer. The patterned porous scaffold comprises a plurality of splitting structures arranged in repeated segments around a central longitudinal axis of the patterned porous scaffold extending from one end to the other of the first fluidic chamber. The patterned porous scaffold promotes chaotic advection of fluid flowing through the patterned porous scaffold, in a general direction along the central longitudinal axis, by splitting and recombining the flow at a plurality of splitting locations along the length of the patterned porous scaffold. The splitting structures split the flow into a plurality of sub-streams at each splitting location, and the sub-streams are subsequently recombined before being split by the next splitting structure at the next splitting location. Each time the flow is split and recombined, it brings different parcels of fluid from the bulk of the flow into contact with the surface of the static mixer element, and splitting the flow multiple times along the length of the static mixer increases the amount of fluid which comes into contact with the patterned porous scaffold. It will be appreciated that the patterned porous scaffold is repeated in each flow channel and in the space between the end of the indent of each flow directing panel and the outer perimeter of the compound static mixer. In some embodiments or examples, at least 75% of the flow channel comprises a patterned porous scaffold defining a plurality of passages configured for mixing the one or more fluidic reactants during flow and reaction thereof. Preferably, at least 90% of the flow channel comprises a patterned porous scaffold defining a plurality of passages configured for mixing the one or more fluidic reactants during flow and reaction thereof. The patterned scaffold may be formed from or comprise a plurality of segments. Each segment comprises a plurality of similar structures separated by a bridging support. In an embodiment, each segment comprises a plurality of apertures and passages defined by a plurality of interlinked elongated polygonal prisms interconnected with bridging supports. The pore size (in mm) of the apertures and passages of the patterned porous scaffold may be in a range between about 0.1 to about 5. In some embodiments or examples, the pore size of the apertures and passages of the patterned porous scaffold may be at least about 0.3 mm. In some embodiments or examples, the pore size of the apertures and passages of the patterned porous scaffold may be less than about 5 mm. In some embodiments, the bridging supports are in two directions. For example, the bridging support may have a criss-cross geometry. In one

particular example, the bridging supports are the same direction as the flow. It will be appreciated that the patterned porous scaffold forms an anchor for the catalyst.

[0063] The compound static mixer element or reactor is generally provided with a high specific surface area (i.e., the ratio between the internal surface area and the volume of the of the first chamber of the compound static mixer element and reactor chamber). The specific surface area ($\text{m}^2 \text{m}^{-3}$) may be in the range of 100 to 40,000, 200 to 30,000, 300 to 20,000, 500 to 15,000, or 12000 to 10,000. The specific surface area ($\text{m}^2 \text{m}^{-3}$) may be at least 100, 200, 300, 400, 500, 750, 1000, 2000, 3000, 4000, 5000, 7500, 10000, 12500, 15000, 17500, or 20000. It will be appreciated that the specific surface areas can be measured by a number of techniques including the BET isotherm techniques.

[0064] The compound static mixer elements may be configured for enhancing properties, such as catalytic reactivity, mixing and heat transfer, for laminar flow rates or turbulent flow rates. It will be appreciated that for Newtonian fluids flowing in a hollow pipe, the correlation of laminar and turbulent flows with Reynolds number (Re) values would typically provide laminar flow rates where Re is <2300 , transient where $2300 < \text{Re} < 4000$, and generally turbulent where Re is >4000 . The compound static mixer elements may be configured for laminar or turbulent flow rates to provide enhanced properties selected from one or more of catalytic reactivity, mixing, degree of reaction, heat transfer, and pressure drop. It will be appreciated that further enhancing a particular type of chemical reaction will require its own specific considerations.

[0065] In one embodiment, the compound static mixer element may be generally configured for operating at a Re of at least 0.01, 0.1, 1, 5, 50, 100, 150, 200, 250, 300, 350, 400, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000. The compound static mixer element may be configured for operating in a generally laminar flow Re range of about 0.1 to 2000, 1 to 1000, 10 to 800, or 20 to 500. The compound static mixer element may be configured for operating in a generally turbulent flow Re ranges of about 1000 to 15000, 1500 to 10000, 2000 to 8000, or 2500 to 6000.

[0066] The volume displacement % of the compound static mixer relative to a reactor chamber for containing the mixer may be in the range of 15 to 50. The volume displacement % of the compound static mixer relative to a reactor chamber for containing the mixer may be less than 50, 45, 40, 35, 30, 25, 20, or 15. The volume displacement % of the compound static mixer relative to a reactor chamber for containing the mixer may be at least 10, 15, 20, 25, 30, 35, 40, 45, or 50. The volume displacement % of the compound static mixer relative to a reactor chamber for containing the mixer may be a range provided by any two of these upper and/or lower values. It will be appreciated that these values are for the volume displacement % of the compound static mixer itself, i.e. without catalyst coating.

[0067] The configurations of the compound static mixers may be provided to enhance cross-sectional microscopic turbulence. Such turbulence may result from various sources, including the geometry of compound static mixer or the microscopic roughness of the compound static mixer surface resulting from the 3D printing process and/or surface coating. For example, turbulent length scales may be reduced to provide better mixing. The turbulent length scales may, for example, be in the range of microscopic length scales.

[0068] The configurations of the static mixers may be provided to enhance heat transfer properties in the reactor, for example a reduced temperature differential at the exit cross-section. The heat transfer of the compound static mixer may, for example, provide a cross-sectional or transverse temperature profile that has a temperature differential of less than about 0.6 °C/mm, 0.5 °C/mm, 0.4 °C/mm, 0.3 °C/mm, 0.2 °C/mm, or 0.1 °C/mm. Preferably, the heat transfer of the compound static mixer may, for example, provide a cross-sectional or transverse temperature profile that has a temperature differential of less than about 0.3 °C/mm. More preferably, the heat transfer of the compound static mixer may, for example, provide a cross-sectional or transverse temperature profile that has a temperature differential of less than about 0.2 °C/mm. Even more preferably, the heat transfer of the compound static mixer may, for example, provide a cross-sectional or transverse temperature profile that has a temperature differential of less than about 0.1 °C/mm.

[0069] The patterned porous scaffold may be configured such that, in use, the pressure drop (i.e. pressure differential or back pressure) across the compound static mixers (in Pa/m) is in a range of about 0.1 to 1,000,000 Pa/m (or 1 MPa/m), including at any value or range of any values therebetween. For example, the pressure drop across the compound static mixer (in Pa/m) may be less than about 500,000, 250,000, 100,000, 50,000, 10,000, 5,000, 1,000, 750, 500, 250, 100, 75, 50, 25, 20, 15, 10, or 5 Pa/m. The compound static mixers may be configured to provide a lower pressure drop relative to a specific flow rate. In this regard, the compound static mixers, reactor, system, and processes, as described herein, may be provided with parameters suitable for industrial application. The above pressure drops may be maintained where the volumetric flow rate is at least 0.1, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50 ml/min.

Process for Preparing a Compound Catalytic Static Mixer

[0070] A process for preparing a catalytic compound static mixer (CCSM) element for a continuous flow chemical reactor chamber may comprise the steps of: providing a compound static mixer element comprising at least a first fluidic chamber comprising a plurality of axially spaced flow directing panels each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define a plurality of separate flow channels, wherein each flow channel extends along the longitudinal axis of the first fluidic chamber and is configured at or near one opposing end for fluidic connection with an adjacent flow channel such that, in use, one or more fluidic reactants entering the first fluidic chamber flow in a serpentine direction through the plurality of separate flow channels, and wherein each flow channel comprises a patterned porous scaffold defining a plurality of passages configured for mixing one or more fluidic reactants during flow and reaction thereof through the patterned porous scaffold such that the patterned porous scaffold links the plurality of flow directing elements; and applying a catalytic coating to the surface of the scaffold to form a catalytic compound static mixer (CCSM) element.

[0071] The compound static mixer element may be provided by additive manufacturing, such as 3D printing. Additive manufacturing of the compound static

mixer and subsequent catalytic coating can provide a compound static mixer that is configured for efficient mixing, heat transfer and catalytic reaction (of reactants in continuous flow chemical reactors). Following original design and development using additive manufacturing, the compound static mixer may be prepared using other manufacturing process, such as casting (e.g. investment casting).

[0072] The compound static mixer elements may be made by the additive manufacture (i.e. 3D printing) techniques. For example, an electron beam 3D printer or a laser beam 3D printer may be used. The additive material for the 3D printing may be, for example, titanium alloy based powders (e.g. 45-105 micrometre diameter range) or the cobalt-chrome alloy based powders (e.g. FSX-414) or stainless steel or aluminium-silicon alloy. The powder diameters associated with the laser beam printers are typically lower than those used with electron beam printers.

[0073] 3D printing is well understood and refers to processes that sequentially deposit material onto a powder bed via fusion facilitated by the heat supplied by a beam, or by extrusion and sintering-based processes. 3D printable models are typically created with a computer aided design (CAD) package. Before printing a 3D model from an STL file, it is typically examined for manifold errors and corrections applied. Once that is done, the .STL file is processed by software called a "slicer," which converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of 3D printer. The 3D printing process is advantageous for use in preparing the compound static mixer elements since it eliminates the restrictions to product design imposed by traditional manufacturing routes. Consequently, the design freedom inherited from 3D printing allows a static mixer geometry to be further optimised for performance than it otherwise would have been.

[0074] Some embodiments relate to a method of forming a catalytic static mixer, the method comprising: coating a scaffold with a catalytic material using a cold spraying process. In some embodiments, the method may first comprise forming the scaffold using an additive manufacturing process, such as 3D printing.

Flow Direction

[0075] The compound static mixer elements as described herein may be configured to allow at least 3 types of flow. Flow during chaotic advection, flow which is in the same direction of the overall flow (net flow) or opposite (180°) to the overall flow and overall flow where the flow from an inlet flows in a serpentine direction according to 2 below in a cylindrical direction before exiting the static mixer element through an outlet. Each of the flow conditions is further described below:

- 1) flow during chaotic advection when a fluidic reactant comes into contact with the patterned porous scaffold and splits the flow of the fluidic reactant into multiple directions, i.e. into a plurality of sub-streams, at a plurality of locations along a flow channel. The diagram in Figure 4a shows tracer transport in laminar and turbulent flows. It will be understood that this is an example of chaotic advection. In the diagram, the straight, parallel black lines are streamlines, which are parallel to the overall (or main) flow. In laminar flow the fluid particles follow the streamlines exactly, as shown by the linear dye trace in the laminar region. In turbulent flow eddies of many sizes are superimposed onto the mean flow. When dye enters the turbulent region it traces a path dictated by both the mean flow (streamlines) and eddies. Larger eddies carry the dye laterally across streamlines. Smaller eddies create smaller scale stirring that causes the dye filament to spread (diffuse). It is the diffusion that creates the local mixing of constituents that are transported to various locations by larger eddies.;

- 2) flow which is in the same direction of the overall flow (net flow) or opposite (180°) to the overall flow when the fluidic reactant undergoing chaotic advection according to 1 above, flows between flow channels through an elongated flow path before it turns and flows into an adjacent elongated flow channel in a serpentine direction. In other words, the flow of fluidic reactants or reaction products according to at least some embodiments or examples described herein serpentine about an axis parallel to the overall direction of flow in a cylindrical pattern (Fig. 4b(iA and B)). The fluid flow pattern shown in Figures 4b(iA) and 4b(iB) is also referred to herein as having a rotated serpentine motion. This is different to flow of a fluidic reactant in a serpentine motion about an axis perpendicular to the direction of flow (main flow), see Fig. 4b(ii), and considered classic serpentine motion; and

- 3) overall flow where the flow from an inlet flows in a serpentine direction according to 2 above in a cylindrical direction before exiting the static mixer element through an outlet. It will be understood that the outlet can be on the same side as the inlet or the opposite side as the inlet.

Patterned Porous Scaffold

[0076] The patterned porous scaffold of the compound static mixer may comprise or consist of at least one of a metal, metal alloy, cermet and metal oxide. The patterned porous scaffold may be a metal scaffold, for example formed from metals or metal alloys. The patterned porous scaffold may be formed from a metal or metal alloy capable of catalytic reactions, such as palladium. The metal scaffold may be prepared from a material suitable for additive manufacturing (i.e. 3D printing). The metal scaffold may be prepared from a material suitable for further surface modification to provide or enhance catalytic reactivity, for example a metal including nickel, titanium, palladium, platinum, gold, copper, aluminium or their alloys and others, including metal alloys such as stainless steel. In one embodiment the metal for the scaffold may comprise or consist of titanium, stainless steel, and an alloy of cobalt and chromium. In another embodiment, the metal for the scaffold may comprise or consist of stainless steel and cobalt chromium alloy. Using additive manufacturing techniques, i.e. 3D metal printing, the metal scaffold can be specifically designed to perform two major tasks: a) to act as a catalytic layer or a substrate or anchor for a catalytic layer, b) to act as a flow guide for optimal mixing performance during the chemical reaction and subsequently assist transfer of exothermic heat to the walls of the reactor tube (single phase liquid stream or multiphase stream) inside the reactor.

[0077] The patterned porous scaffold may comprise or consist of a metal selected from at least one of iron, aluminium, cobalt, copper, zinc, nickel, palladium, platinum, gold, silver, ruthenium, iridium, rhodium, titanium vanadium, zirconium, niobium, tantalum, and chromium, or a metal alloy, cermet or metal oxide thereof. The patterned porous scaffold may comprise or consist of titanium, aluminium, nickel, iron, silver, cobalt, chromium, or an alloy thereof. The patterned porous scaffold may comprise or consist of titanium, titanium alloy or stainless steel. The titanium alloy may comprise

aluminium and vanadium, for example. Non-limiting examples of other transition metals that may be used in metal alloys are zirconium, niobium and tantalum.

[0078] In an embodiment, the patterned porous scaffold comprises at least one of a metal, semi-metal and metal oxide. For example, the patterned scaffold may comprise one or more of the following: a metal selected from iron, cobalt, chromium, aluminium, vanadium, copper, zinc, nickel, palladium, platinum, gold, silver, ruthenium, iridium, and rhodium, or alloys or mixtures thereof; a semimetal selected from Bi, CdTe, HgCdTe, GaAs, or mixtures thereof; and a metal oxide selected from PbO, PbO₂, ZnO, TiO₂, CoO, Al₂O₃, or mixtures thereof.

Catalyst Material

[0079] Catalytically reactive sites of the patterned porous scaffold may be provided by at least one of the following: the patterned porous scaffold being formed from a catalytic material; a catalyst material being intercalated, interspersed and/or embedded with at least part of the patterned porous scaffold; and at least a part of the surface of the patterned porous scaffold comprising a coating comprising a catalyst material or a catalyst support material comprising the catalyst material on a support material. In one embodiment, the catalytically reactive sites are provided by a coating comprising a catalyst material or a catalyst support material comprising the catalyst material on a support material on the scaffold. For example, the catalytically reactive sites may be provided by a dip coating comprising a catalyst material or a catalyst support material comprising the catalyst material on a support material on the patterned scaffold.

[0080] The catalytically active patterned scaffold may be prepared from a catalytic material selected from at least one of a metal, metal alloy, cermet and metal oxide. The process of preparing a compound static mixer may comprise a step of applying a coating comprising the catalytic material or a catalyst support material comprising the catalyst material on a support material onto at least a substantial portion of the patterned scaffold by any suitable coating means, such as electrodeposition or dip coating, preferably the coating is a dip coating. For example, the coating may be provided on at least 50 % of the surface of the patterned porous scaffold. In other

embodiments, the coating may be provided on at least 60%, 70%, 80%, 90%, 95%, 98, or 99%, of the surface of the patterned porous scaffold.

[0081] It will be appreciated that the catalyst material may be selected and varied based on a particular reaction or application required. In some embodiments, the catalyst material or catalyst supported material may be selected to provide for dehydrogenation reactions in a continuous flow reactor environment. In other embodiments, the catalyst material or catalyst supported material may be selected to provide for heterogeneous catalysis reactions in a continuous flow reactor environment. A wide range of heterogeneous catalysis chemical reactions may be provided for by selection from a wide range of catalytic materials, including but not limited to the following: hydrogenations using hydrogen gas, transfer hydrogenations using a liquid hydrogen donor, catalytic oxidations such as dehydrogenations, reductive aminations, carbon-carbon couplings including Suzuki, Sonogashira, Heck, Stille, Negishi, Ullmann, Kumada couplings and other metal catalysed organic transformations.

[0082] The surface of the patterned porous scaffold may be modified to provide or enhance catalytic reactivity, such as by roughening, and/or depositing a metal or alloy on at least a part of the surface of the scaffold, such as a further deposited (sputtered) layer. Surface roughening may be achieved by any process of acid treatment, heat treatment in controlled gas atmospheres, physical vapour deposition, cold spray, plasma spray, ion implantation flame spray pyrolysis electrodeposition, chemical vapour deposition, glow discharge, sputtering, and plating or by any mechanical means. The surface modification may provide one or more outer layers, for example one or more metal deposited (e.g. sputtered) layers.

[0083] A catalytic material or catalytic support material may refer to a catalyst by itself or to a material or composition comprising a catalyst. The catalytic material or catalytic support material may be provided in a composition with one or more additives, such as binders, to facilitate coating of the catalyst to the scaffold. The binders can include, but are not limited to, organic materials (such as PEI, HPMC or HPC) and inorganic materials (such as water glass, aluminium chloride, and a mixture of colloidal silica with aluminium dihydrogen phosphate, alumina sol, silica sol, the

colloidal sol of pseudo boehmite and aluminium phosphate sol, etc., kaolin, alumina, aluminosilicate clay, colloidal silica, bentonite, kaolinite).

[0084] The catalyst or coating thereof may be provided as a partial coating or a complete layer on the scaffold. The coating or layer of the catalyst on the patterned porous scaffold may be provided in one or more layers. The catalyst material or catalyst support material may be deposited on the scaffold by dip coating, brush coating, painting, slurry spraying, spray pyrolysis, sputtering, chemical or physical vapour deposition techniques, electroplating, screen printing, tape casting, electro-deposition, flame spraying, arc spraying, plasma spraying, detonation spraying, high velocity oxy-fuel flame spraying, laser spraying,. In one particular example, the catalyst material or catalyst support material may be deposited on the patterned porous scaffold by a dip coating method, such as that described in PCT/AU2020/050464.

[0085] It will be appreciated that the catalytic material, catalyst support material, or composition or coating thereof, may include one or more additives. The additives may include catalysts or promoters to enhance reaction rates at the patterned scaffold or compound static mixer surface. The one or more additives may be incorporated within the scaffold itself (such as by doping), for example by addition to additive manufacturing material. Promoters may include materials with a low electronegativity. Suitable promoters may be selected from alkali metals (K, Cs) and alkali earths (mostly Ba). It will be appreciated that exceptions may include the rare earths (La, Ce and Sm) that have a moderately high electronegativity.

[0086] In one embodiment, the catalyst may be in the form of catalyst particles formed from a catalyst material. In another embodiment, the catalyst is in the form of a catalyst supported material comprising the catalyst material on a support material. In some embodiments, the catalyst supported material is in the form of particles.

[0087] In one embodiment or example, the catalyst particles are formed from a catalyst material or a catalyst supported material comprising the catalyst material on a support material. In an embodiment or example, the catalyst particles may be in a range from 0.1 nm to 10 mm, 1 nm to 5 mm, 100 nm to 1 mm, 1 μ m to 200 μ m, 0.25 μ m to 50 μ m, or 0.5 μ m to 5 μ m. The catalyst particles may be less than 5 mm, 1 mm, 100

μm , 10 μm , 5 μm , 1 μm , 500 nm, 250 nm, 100 nm, or 50 nm. The catalyst particles may be at least 0.1 nm, 1 nm, 10 nm, 100 nm, 250 nm, 1 μm , 2 μm , 3 μm , 4 μm , 5 μm , 10 μm , 15 μm , 20 μm , 25 μm , or 50 μm . The catalyst particles may be a range provided by any two of these upper and/or lower values. It will be appreciated that the size of the catalyst particles are controlled by dry or wet milling if required. For example, the catalyst particles are less than 5 μm . It will also be appreciated that the catalyst particles formed from the catalyst material or the catalyst supported material are controlled by dry or wet milling if required. For example, the catalyst material or the catalyst supported material are less than 5 μm . In an embodiment or example, the catalyst particles may be in the form of spheres, pellets, cylinders, trilobes, honeycomb, plate, and quadralobes.

[0088] In another embodiment or example, the catalyst particles may be ex-situ catalyst particles. For example, an ex-situ catalyst may include a catalyst prepared such that the catalyst particles are in their final form prior to deposition to a surface of a scaffold. The catalyst particles in the catalytic liquid may be considered ex-situ if they have at least some catalytic activity irrespective of any activation reaction such as calcination. It will be appreciated that an ex-situ catalyst may differ from an in-situ catalyst. An in-situ catalyst may be a catalyst precursor applied to a surface of a scaffold which requires a further treatment step to produce the active catalyst in its final form, e.g. via activation such as calcination.

[0089] In some embodiments or examples, the catalyst material or catalyst support material may be selected from any one or more catalysts known in the art including, but not limited to, metal catalysts (e.g. Ru-based catalyst, Pd-based catalysts, Pt-based catalysts, Ni-based catalysts, Cr-based catalysts, Co-based catalysts, Zn-based catalysts, etc.), bi-metallic catalysts (e.g. Ru-Ni based catalysts, Ru-Pd based catalysts, Pt-Co based catalysts, Pt-Ni based catalysts, Pt-Pd based catalysts, Cu-Pt based catalysts, Ru-La based catalysts, Co-Cu, Pt-Ru, Cu-Ni, Ir-Zn, Zn-Ti, Cr-Al, etc.), metal oxide catalysts, metal ligand complex catalysts, sol catalysts, sulfur-poisoned metal catalysts, etc. Single atom catalysts can also be considered very effective for heterogeneous catalysis reactions as catalyst materials. A person skilled in the art will understand how to incorporate these materials into a compound static mixer. The catalyst material may

be modified in order to improve selectivity, activity and lifetime of the catalyst. The modification may be made by introducing different chemical moieties. For example, previous studies have shown that this can be achieved by: (a) adding selectivity promoters, b) using bimetallic catalyst systems, or c) using mixed oxide supports for distribution of metal.

[0090] It will be appreciated that the support material may be selected from, but not limited to, at least one of activated carbon, mesoporous carbon, graphene, graphitic material, metal-organic framework, zeolite, aluminium oxide, silicon dioxide, ceramic, etc. When a catalyst material is used as a support material, the catalyst material and support material would be different.

[0091] In some embodiments, the catalytic material or catalytic support material may further comprises a binder. In an embodiment or example, the binder can be selected from the group comprising hydroxypropyl cellulose, methyl cellulose, polyester, polyurethane, acrylic resins, condensation resins, polyvinyl acetate, poly(acrylic acid) sodium salt, polyvinylidene fluoride, polyethylene oxide, polyethylene glycol, dextrin, sodium silicate, colloidal silica, polydimethyl siloxane, boehmite, colloidal aluminium oxide or polyisobutylene. The binder may be hydroxypropyl cellulose, sucrose, dextrin, or starch. The binder may be hydroxypropyl cellulose, polyvinyl acetate, polyethylene glycol, sodium silicate or colloidal silica. The binder may be hydroxypropyl cellulose, polyvinyl acetate or colloidal silica. The binder may be hydroxypropyl cellulose, polyvinyl acetate or polydimethyl siloxane. The binder may be boehmite or colloidal aluminium oxide.

[0092] In some embodiments, the total amount of binder present in the coating composition may be in a range of between about 5 wt.% to about 15 wt.% (based on the total weight of the coating composition), preferably about 6 wt.% to about 12 wt.%, most preferably about 8 wt.% to about 10 wt.%. The amount of binder (in wt.% based on the total weight of the coating composition) present in the catalyst composition may be less than about 15, 14, 13, 12, 10, 9, 8, 7, 6, or 5. The amount of binder (in wt.% based on the total weight of the coating composition) present in the catalyst composition may be at least about 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, or 15.

[0093] In one embodiment, the patterned porous scaffold is a patterned metal scaffold comprising a coating comprising catalytic material or catalytic support material. In another embodiment, the patterned metal scaffold comprises titanium, nickel, aluminium, stainless steel, cobalt, chromium, any alloy thereof, or any combination thereof. In another embodiment, the patterned metal scaffold comprises at least one of a stainless steel and aluminium. In another embodiment, the patterned metal scaffold comprises titanium, or a titanium alloy. Further advantages may be provided wherein the patterned metal scaffold comprises or consists of stainless steel.

[0094] In one embodiment, the catalytically active scaffold is a patterned stainless steel scaffold, and the surface of the patterned scaffold is provided with a dip coating comprising platinum on aluminium oxide as the catalyst support material.

[0095] The weight % of the coating or catalyst material or catalyst support material, based on total weight of compound static mixer, may be in the range of 0.5 to 40%, 1 to 35%, 2 to 30%, 5 to 25 %, or 10 to 20%. The weight % of the coating comprising the catalyst material, based on total weight of compound static mixer, may be at least 0.5%, 1%, 2%, 5%, 10%, 15%, 20%, 35%, 30%, 35%, or 40%. The weight % of the coating comprising the catalyst material, based on total weight of compound static mixer, may be less than 50%, 40%, 30%, 20%, 15%, 10%, 5%, 3%, 2%, 1%, 0.5%.

Continuous Flow Systems and Reactors

[0096] The present disclosure provides a continuous flow chemical reactor for use in catalytic reactions of one or more fluidic reactants. The compound static mixer element can be configured for inserting into a continuous flow chemical reactor, which may be referred to as a “compound static mixer insert” or “catalytic compound static mixer” when the compound static mixer comprises a catalyst material or catalyst support material. In an embodiment, there is provided a continuous flow chemical reactor for use in reaction of one or more fluidic reactants, the reactor comprising: the compound static mixer element of any one of embodiments described herein; a reactor chamber configured for receiving and housing the compound static mixer element; at least one reactant inlet for supply of the one or more fluidic reactants to the reactor chamber section; and at least one outlet in fluidic communication with the static mixer for

receiving an output stream comprising a product of the reaction, wherein the inlet and outlet is separated by the static mixer element, and wherein the static mixer element disposed within the reactor chamber is configured for dispersing and mixing the one or more fluidic reactants during flow and reaction thereof through the mixer.

[0097] It will be appreciated that the compound static mixer is an integral part of the chemical reactor. The compound static mixer and reactor chamber together form the reactor, which may be provided as a single unit. The reactor chamber may provide the housing for the compound static mixer. The reactor chamber may optionally include a heat exchanger system, which may be used for controlling heat removed from the reactor chamber during its operation. The reactor may comprise at least one heat exchanger system to allow control of the temperature of the reactor, compound static mixer element, or fluidic components thereof. In some embodiments, the heat exchanger system may comprise a controller to control the temperature of the reactor, static mixer element, or fluidic components thereof. The reactor chamber may include a compound static mixer element or a catalytic compound static mixer element, one or more heat exchanger systems, etc., and combinations thereof.

[0098] An embodiment of the continuous flow chemical reactor is depicted in Figure 2. The compound static mixer element or catalytic compound static mixer element (10) is housed in a reaction chamber (11). The reactor further comprises a fluid inlet to for supply of the one or more fluidic reactants to the reactor chamber section. Also provided is a fluid outlet in fluidic communication with the reaction chamber section for receiving an output stream comprising a product of the reaction. It will be appreciated that the inlet and outlet is separated by the static mixer element. The rod heat exchanger unit (14) is configured to allow control of the temperature of the reactor, compound static mixer element, or fluidic components thereof.

[0099] In an embodiment, the reactor may further comprise at least one flange (16,17), at least one gasket (18,19), and at least one blind flange (20,21) to seal the reactor, wherein the at least one gasket (18,19) is fitted in between the at least one flange (16,17) and at least one blind flange (20,21), as shown in Figure 3. For example, the reactor may comprise at least one flange (16,17), at least one gasket (18,19), and at least one blind flange (20,21) to seal the reactor at each end of the reactor.

[0100] It will be appreciated that the compound static mixer, or reactor thereof, may comprise one or more reactant inlets (12) for supply of one or more fluidic reactants to a reactor chamber, and one or more outlets (13) in fluid communication with the compound static mixer for receiving an output stream comprising a product or products of the reaction (for example as depicted in Figure 2). It will be appreciated that at least one thermal couple may be used to monitor the temperature. For example, at least one thermal couple may be positioned: (a) inside the first reactor chamber to monitor the temperature of the one or more fluidic reactants as it passes through the plurality of separate flow channels, (b) at the one or more outlets to monitor the temperature of the output stream comprising a product or products of the reaction, (c) at the gasket between the flanges of the reactor, (d) at one end of the heat rod housed inside the second reactor chamber, or (e) a combination thereof.

[0101] In one embodiment, the continuous flow chemical reactor is a tubular flow reactor.

[0102] In another embodiment, the reactor comprises at least one heat exchanger for controlling the temperature of the reactor, reactor chamber, catalytic compound static mixer, fluidic components, or combinations thereof. The heat exchanger may be a shell, tube, or rod heat exchanger design or configuration. The heat exchanger may be a rod heat exchanger housed in the second reactor chamber.

[0103] In an embodiment, the aspect ratios of the reactor may, for example, be similar to those previously described for the compound static mixer such that a compound static mixer element may be configured for insertion into the reactor. In one example, the aspect ratio (L/d) of the reactor can be less than about 150, 140, 130, 120, 110, 100, 90, 80, 70, 60, 50, 40, 30, 20, or 10. In another example, the aspect ratio (L/d) of the reactor can be at least about 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, or 150. The aspect ratio (L/d) of the reactor may be a range provided by any two of these upper and/or lower values.

[0104] The present disclosure also provides a system for a continuous flow chemical reaction process comprising: a continuous flow chemical reactor comprising a compound static mixer according to any of the embodiments described herein; a pump

for providing fluidic flow for one or more fluidic reactants and any products thereof through the reactor; one or more heat exchangers for controlling the temperature of the reactor, reactor chamber, compound catalytic static mixer, or fluidic components thereof; and a control means for controlling one or more of the parameters of the system selected from concentration, flow rate, temperature, pressure, and residence time, of the one or more fluidic reactants, sources of fluidic reactants, carrier fluids, or products of the reaction.

[0105] The system may further comprise a cooling system for cooling the output stream comprising a product of the reaction.

[0106] The system may comprise at least one filter to remove particulates from the one or more fluidic reactants prior to the reactant inlet and/or to remove catalyst material or catalyst support material in the output stream comprising a product of the reaction.

[0107] The system may further comprise at least one membrane for separation of products. It will be appreciated that a separation membrane may be used to filter out any unwanted products or filter out hydrogen from other gases, for example, vanadium based separation membranes known in the art.

[0108] The system may further comprise a dispersing unit, which can be configured before and/or after the reactor chamber, for dispersing the one or more fluidic reactants.

[0109] The system may further comprise a spectrometer, which can be used for identifying and determining concentrations for any one or more fluidic reactants or products thereof.

[0110] It will be appreciated that the system, reactor, or each chamber section, may include one or more inlets and outlets to provide supply of reactants, obtain products, or to recirculate various reactants and/or products.

[0111] It will also be appreciated that the reactor or system may be designed for recycling of the various reactants, reactant sources, intermediary products, or desired products provided to and produced in the reactor chamber. The reactor or system may be provided in various designs and forms, for example in the form of a tubular reactor.

In another embodiment, the reactor is a multiple pass reactor. In other words, the compound static mixer element may comprise: at least a first fluidic chamber comprising a plurality of axially spaced flow directing panels each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first chamber to define a plurality of separate flow channels, wherein each flow channel extends along the longitudinal axis of the first fluidic chamber and is configured at or near one opposing end for fluidic connection with an adjacent flow channel such that, in use, one or more fluidic reactants entering the first chamber flow in a serpentine direction through the plurality of separate flow channels. In some embodiments, the compound static mixer may comprise between 2 and 10 axially spaced flow directing panels defining between 2 and 10 separate flow channels respectively. For example, the compound static mixer may comprise 6 axially spaced flow directing panels defining 6 separate flow channels respectively.

[0112] The system and processes may also be integrated into more complex systems, such as systems and processes comprising a coal gasifier, electrolyser and/or natural gas reformer etc.

Catalytic Processes and Reactions

[0113] The compound static mixer is for use in a continuous flow chemical reaction system and process.

[0114] As mentioned above, the chemical reactor comprising the catalytic compound static mixer element is capable of performing heterogeneous catalysis reactions in a continuous fashion. The chemical reactor may use single or multi-phase feed and product streams. In one embodiment, the substrate feed (comprising one or more reactants) may be provided as a continuous fluidic stream, for example a liquid stream containing either: a) the substrate as a solute within an appropriate solvent, or b) a liquid substrate, with or without a co-solvent. It will be appreciated that the fluidic stream may be provided by one or more gaseous streams, for example a hydrogen gas or source thereof. The substrate feed is pumped into the reactor using pressure driven flow, e.g. by means of a piston pump.

[0115] The present disclosure also provides a process for synthesizing a product by catalytic reaction of one or more fluidic reactants, the process comprising the steps of: providing a continuous flow chemical reactor comprising a compound static mixer element or system according to any of the embodiments described herein; providing at least a first fluidic reactant to the reactor via the one or more reactant inlets; operating the chemical reactor, or control means thereof, to provide flow and catalytic reaction of the at least first fluidic reactant through the catalytic compound static mixer; and obtaining an output stream comprising a product of a catalytic reaction of the at least first reactant.

[0116] The process may be for synthesizing a product by heterogeneous catalytic reaction of at least a first fluidic reactant with a second fluidic reactant, which may comprise: providing a continuous flow chemical reactor comprising a catalytic compound static mixer element or system according to any of the embodiments described herein; providing at least a first and second fluidic reactants, or source thereof, to the reactor via the one or more reactant inlets; operating the chemical reactor, or control means thereof, to provide flow and catalytic reaction of the first and second fluidic reactant through the static mixer; and obtaining an output stream comprising a product of a catalytic reaction of at least the first and second fluidic reactants.

[0117] It will be appreciated that various parameters and conditions used in the process, such as temperatures, pressures and concentration/amounts of materials and reactants, may be selected depending on a range of variables of the process including the product to be synthesised, chemical reaction or mechanisms involved, reactant source, selection of catalyst(s) used, or type of reactor being used and materials and configuration thereof. For example, differences will exist where the one or more fluidic reactants, or co-solvents (e.g. inert carriers) etc., are gases, liquids, solids, or combinations thereof. For example, one or more fluidic reactants may be provided in a fluidic carrier, such as a solute reactant in liquid carrier or particularised reactant in a carrier gas. The one or more fluidic reactants may be provided as a gas, for example a gas comprising molecular hydrogen or a source of hydrogen.

[0118] Temperatures (°C) in relation to the process may be in a range between -50 and 400, or at any integer or range of any integers there between. For example, the temperature (°C) may be at least about -50, -25, 0, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, or 700. For example, the temperature (°C) may be less than about 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, or 50. The temperature may also be provided at about any of these values or in a range between any of these values, such as a range between about 0 to 700°C, about 25 to 600°C, or about 50 to 500°C.

[0119] The process may involve a mean residence time in the static mixer or reactor in a range of about 1 second to about 5 hours. The mean residence time (in minutes) may, for example, be less than about 300, 250, 200, 150, 120, 100, 80, 60, 45, 30, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.5 or 0.1. The mean residence time (in minutes) may, for example, be greater than about 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 30, 45, 60, 80, 100, 120, 150, 200, or 250. The mean residence time may be provided as a range selected from any two of these previously mentioned values. For example, the mean residence time may be in a range of 2 to 10, 3 to 8, 4 to 7, or 5 to 6 minutes.

[0120] The process may provide a product conversion rate (% reactant converted to product) of at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 98, 99%, 99.5% or 99.9%. It will be appreciated that the product conversion rate (% reactant converted to product) may be dependent on the system temperature.

[0121] The process may involve a heterogeneous catalytic reaction selected from hydrogenations, oxidations (e.g. dehydrogenations), carbon-carbon couplings, and reductive aminations. In one embodiment, the heterogeneous catalytic reaction is a hydrogenation reaction. In another embodiment, the heterogeneous catalytic reaction is a dehydrogenation reaction. It will be appreciated that hydrogenation reactions will involve at least a first fluidic reactant being hydrogen and a second reactant being an organic compound capable of hydrogenation. Alternatively, the second reactant being a nitrogen gas or oxygen gas such that the product of the hydrogenation reaction is ammonia or hydrogen peroxide. The hydrogen source may be hydrogen gas (molecular hydrogen) or a liquid hydrogen donor. A pre-step for hydrogenation may be introducing hydrogen gas for pre-activation, for example at a lower flow rate before

introducing an organic compound capable of hydrogenation. It will be appreciated that dehydrogenation reactions will involve introducing a hydrogen carrier into a continuous flow chemical reactor comprising a compound static mixer element; (ii) dehydrogenating the hydrogen carrier as it passes through the reactor whereby said dehydrogenating produces hydrogen and a dehydrogenated carrier; (iii)(a) obtaining an output stream comprising hydrogen and the dehydrogenated carrier; and (iv) separating hydrogen and the dehydrogenated carrier..

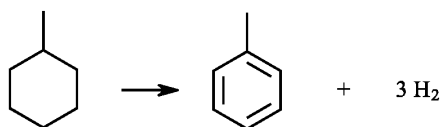
[0122] For heterogeneous reactions involving mixtures of gases and liquids, the gas:liquid ratio (volume/volume) may be at least 1:1, 2:1, 3:1, 4:1, 5:1, 6:1, 7:1, 8:1, 9:1, 10:1, 11:1, 12:1, 13:1, 14:1, or 15:1. The gas:liquid ratio (volume/volume) may be less than 15:1, 14:1, 13:1, 12:1, 11:1, 10:1, 9:1, 8:1, 7:1, 6:1, 5:1, 4:1, 3:1, or 2:1. The gas:liquid ratio (volume/volume) may be provided as a range selected from any two of these previously mentioned values. For example, the gas:liquid ratio may be in a range of 2:1 to 6:1.

[0123] The catalyst material or catalyst support material on the compound static mixer may require a chemical or physical (heating) pre-activation process step, for example for hydrogenations pre-activating by exposure of the catalyst material to molecular hydrogen or a source of hydrogen. In one embodiment, the catalyst material on the patterned scaffold is pre-activated, for example by contacting with an activating fluid (e.g. hydrogen gas) for at least 1, 2, 5, 10, 15, 20, 25 or 30 minutes. The pre-activation may occur for less than 30, 25, 20, 15, 10, 5, 2, or 1 minutes. The pre-activation may occur for less than 30, 25, 20, 15, 10, 5, 2, or 1 minute. The pre-activation may occur between a range of any two of the above time values.

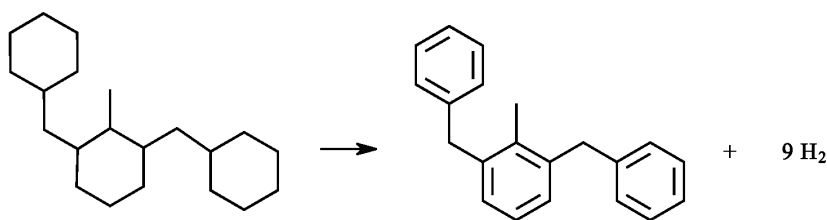
[0124] The catalytic reactions may be hydrogen insertion reactions that involve the use of hydrogenation catalysts. The catalytic reactions may be hydrogen removal reactions that involve the use of dehydrogenation catalysts. Ammonia cracking is a form of dehydrogenation for converting ammonia back to hydrogen. A hydrogenation catalyst facilitate the insertion of hydrogen into intramolecular bonds of a reactant, e.g., a carbon-oxygen bond to form the oxygen containing organic materials described above, conversion of unsaturated bonds to saturated bonds, removal of protection groups such as converting O-benzyl groups to hydroxyl groups, or reaction of a

nitrogen triple bond to form ammonia or hydrazine or mixtures thereof. A dehydrogenation catalyst facilitates the removal of hydrogen from an organic hydrocarbons, e.g., conversion of alkane to alkene. It is the reverse of hydrogenation. The hydrogenation or dehydrogenation catalyst may be chosen from any known hydrogenation or dehydrogenation catalyst known in the art, as described above. For example, catalysts that may be effective for ammonia cracking, include, but is not limited to, metals such as Ru, Fe, Ni, Ir, Mo, Co, Pt, Pd, Rh, Co-Mo, Ni-Mo, Fe-Mo, Ni-Co, Co-Mo-Fe-Ni-Cu, Mg-Fe, Fe-Co, Ni-Fe, Mg-Co-Fe, Ni-Pt, Ni-Pd, Ir-Ni, Cu-Zn, Cu-based catalysts, bimetallic compositions with Ru, and Ni supported on alumina. In a further embodiment, the hydrogenation or dehydrogenation catalyst is coated using dip coating or electro-deposition.

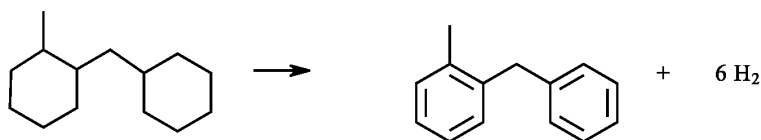
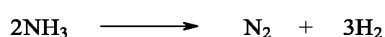
[0125] The following reaction schematics provide some example dehydrogenation reactions:



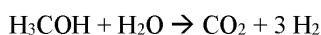
Scheme 1: methyl cyclohexane (MCH) to toluene (Tol)



Scheme 2: perhydro-dibenzyltoluene (H₁₈-DBT) to dibenzyl toluene (DBT)

Scheme 3: perhydro-benzyltoluene (H₁₂-DBT) to benzyl toluene (BT)Scheme 4: ammonia (NH₃) to nitrogen gas (N₂)

[0126] The following reaction schematics provide some example steam reforming processes:

Scheme 5: methanol to carbon dioxide (CO₂)Scheme 6: dimethyl ether (DME) to carbon dioxide (CO₂).

Method of dehydrogenation and hydrogenation

[0127] In one embodiment or example, there is provided a process for releasing hydrogen from a hydrogen carrier comprising (i) introducing the hydrogen carrier into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein; (ii) dehydrogenating the hydrogen carrier as it passes through the reactor whereby said dehydrogenating produces hydrogen and a dehydrogenated carrier; (iii)(a) obtaining an output stream comprising hydrogen and the dehydrogenated carrier; and (iv) separating hydrogen and the dehydrogenated carrier. The hydrogen carrier may be liquid organic hydrogen carriers (LOHC), hydrogen peroxide or ammonia. In an embodiment or

example, there is provided a process for releasing hydrogen from a hydrogen carrier comprising (i) introducing the hydrogen carrier into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein; (ii) dehydrogenating the hydrogen carrier as it passes through the reactor whereby said dehydrogenating produces hydrogen and a dehydrogenated carrier; (iii)(a) obtaining an output stream comprising hydrogen and the dehydrogenated carrier; and (iv) separating hydrogen and the dehydrogenated carrier, wherein the hydrogen carrier may be liquid organic hydrogen carriers (LOHC), hydrogen peroxide or ammonia. In an embodiment or example, there is provided a process for releasing hydrogen from a liquid organic hydrogen carrier (LOHC) comprising (i) introducing a liquid organic hydrogen carrier (LOHC) into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein; (ii) dehydrogenating the LOHC as it passes through the reactor whereby said dehydrogenating produces hydrogen and oxygen; (iii)(a) obtaining an output stream comprising hydrogen and a dehydrogenated carrier; and (iv) separating hydrogen and the dehydrogenated carrier. In another embodiment or example, there is provided a process for releasing hydrogen from a hydrogen peroxide comprising (i) introducing hydrogen peroxide into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein; (ii) dehydrogenating the hydrogen peroxide as it passes through the reactor whereby said dehydrogenating produces hydrogen and oxygen; (iii)(a) obtaining an output stream comprising hydrogen and oxygen; and (iv) separating hydrogen and oxygen. In yet another embodiment or example, there is provided a process for releasing hydrogen from ammonia comprising (i) introducing ammonia into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein; (ii) dehydrogenating the ammonia as it passes through the reactor whereby said dehydrogenating produces hydrogen and nitrogen; (iii)(a) obtaining an output stream comprising hydrogen and nitrogen; and (iv) separating hydrogen and nitrogen. In embodiments, the process enables the removal of hydrogen gas from the compound catalytic static mixer.

[0128] The hydrogen carrier may be in liquid, solid or gas form. In an embodiment or example, the hydrogen carrier may be in liquid form, including but not limited, to liquid organic hydrogen carriers (LOHC), hydrogen peroxide or ammonia. Some examples of LOHCs may include, but not limited to, perhydro-dibenzyltoluene (H₁₈-DBT), perhydro-benzyltoluene (H₁₂-BT), methylcyclohexane (MCH), etc. In a further embodiment, the hydrogen carrier may be in a gas form, including but not limited to, dimethyl ether, methane, butane, propane, or ammonia. In yet another embodiment, the hydrogen carrier may be in a solid form, such as inorganic solids including, but not limited to, sodium borohydride, or magnesium hydride.

[0129] The dehydrogenated carrier (or spent carrier) produced by the dehydrogenation reaction may be in a liquid or gaseous phase. In an embodiment or example, the dehydrogenated carrier produced by the dehydrogenation reaction of a LOHC may be in a liquid phase. In a further embodiment, the dehydrogenated compound produced by the dehydrogenation reaction of ammonia may be in a gas phase. In yet a further embodiment, the dehydrogenated compound produced by the dehydrogenation reaction of hydrogen peroxide may be in a gas phase.

[0130] In some embodiments, the hydrogen carrier may be maintained at a predetermined temperature to provide optimum catalytic reaction conditions. In an embodiment, in step (ii), the temperature of the hydrogen carrier may be maintained between about 20°C and 1000 °C while it passes through the compound catalytic static mixer element.

[0131] In an embodiment, step (iii)(a) further comprises step (iii)(b) wherein the output stream comprising hydrogen and the dehydrogenated carrier passes through an optional cooling system. It will be appreciated that the optional cooling system helps separate the hydrogen from the dehydrogenated carrier. The optional cooling system may be used for separation of the liquid/gas phase (i.e. capture spent (dehydrogenated) carrier). It will be appreciated that some dehydrogenated carriers (i.e. the spent carrier) can be re-hydrogenated and re-used. In some embodiments, it may be preferable to use a separator to avoid the need for a cooling system. Various separators known in the art may be used, such as for example, vanadium based separation membranes.

[0132] In some embodiments, the process may further comprise optionally flushing the reactor with a stream of inert gas, preferably nitrogen (N₂) gas, prior to introducing the hydrogen carrier.

[0133] In some embodiments, the process may further comprise passing the hydrogen carrier through a first filter to remove particulates from the hydrogen carrier prior to step (i).

[0134] In some embodiments, the process may also further comprise passing the dehydrogenated carrier through a second filter to remove catalyst material or catalyst support material in the output stream prior to dehydrogenated carrier passes through a cooling system in step (iii)(b).

[0135] The process may provide a product conversion rate (% hydrogen carrier converted to dehydrogenated carrier) of at least 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 99, 99.5, or 99.9%.

[0136] In some embodiments, the hydrogen produced in the output stream may be re-introduced into the continuous flow chemical reactor with a second fluidic reactant, wherein the second fluidic reactant may be an organic compound capable of hydrogenation. It will be appreciated that the process may be a reversible system. It will also be appreciated that the spent carrier (dehydrogenated carrier) may be re-introduced into the continuous flow chemical reactor with a stream of hydrogen to be re-hydrogenated and re-used in dehydrogenation reactions.

[0137] In another embodiment or example, there is provided a process for synthesizing a product by hydrogenation reaction of at least a first fluidic reactant with a second fluidic reactant, the process comprising: (i) introducing at least a first and second fluidic reactant, or source thereof, into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein via the one or more reactant inlets; (ii) operating the reactor, or control means thereof, to provide flow and hydrogenation reaction of the first and second fluidic reactant through the compound catalytic static mixer; and (iii) obtaining an output stream comprising a product of a hydrogenation reaction of at least the first and second fluidic reactants.

[0138] In an embodiment, the at least first fluid reactant may be hydrogen gas (molecular hydrogen) or a liquid hydrogen donor. The at least second fluidic reactant may be an organic compound capable of hydrogenation. Alternatively, the second fluidic compound may be oxygen gas or nitrogen gas. For example, the product synthesized by the hydrogenation reaction may be hydrogen peroxide or ammonia. In an embodiment, there is provided a process for synthesizing a product by hydrogenation reaction of at least a first fluidic reactant with a second fluidic reactant, the process comprising: (i) introducing at least a first and second fluidic reactant, or source thereof, into a continuous flow chemical reactor comprising a compound catalytic static mixer element as described by any one or more embodiments or examples herein via the one or more reactant inlets; (ii) operating the reactor, or control means thereof, to provide flow and hydrogenation reaction of the first and second fluidic reactant through the compound catalytic static mixer; and (iii) obtaining an output stream comprising a product of a hydrogenation reaction of at least the first and second fluidic reactants, wherein the first fluidic reactant may be hydrogen and the second fluidic reactant may be oxygen or nitrogen. In an embodiment, the product synthesized by the hydrogenation reaction may be hydrogen peroxide. In another embodiment, the product synthesized by the hydrogenation reaction may be ammonia.

[0139] In some embodiments, in step (ii), the temperature of the first and second fluid reactants may be maintained between about 10°C and 300°C while it passes through the compound catalytic static mixer element.

[0140] The process may involve a mean residence time in the compound catalytic static mixer or reactor. The mean residence time in the compound catalytic static mixer or reactor may be in a range of about 1 second to about 5 hours. The mean residence time (in minutes) may, for example, be less than about 300, 250, 200, 150, 120, 100, 80, 60, 45, 30, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.5 or 0.1. The mean residence time (in minutes) may, for example, be greater than about 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 30, 45, 60, 80, 100, 120, 150, 200, or 250. The mean residence time may be provided as a range selected from any two of these previously mentioned values. For example, the mean residence time may be in a range of 2 to 10, 3 to 8, 4 to 7, or 5 to 6 minutes.

[0141] The process may involve a system pressure (in bar). In an embodiment, the pressure (in bar) of the reactor system may be in the range of about 1 to 100. The pressure (in bar) may, for example, be less than about 100, 95, 90, 85, 80, 75, 70, 65, 60, 55, 50, 45, 40, 35, 30, 25, 20, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1. The pressure (in bar) may, for example, be greater than about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, or 100. The pressure may be provided as a range selected from any two of these previously mentioned values.

Dehydrogenation reactions

[0142] The dehydrogenation process using a hydrogen carrier, as described herein, may be for dehydrogenating any saturated hydrocarbon known in the art. Dehydrogenation is the process by which hydrogen is removed from a carrier to form a dehydrogenated carrier (e.g., to convert saturated into unsaturated hydrocarbons), also known as a spent carrier. It will be appreciated that the dehydrogenation process, as described herein, using a hydrogen carrier such as hydrogen peroxide or ammonia, can be used to obtain hydrogen by dehydrogenating the hydrogen peroxide or ammonia.

[0143] One or more advantages of the present disclosure may be provided by the selection of hydrogen carriers such as high hydrogen storage capacities, high conversions rates, lower dehydrogenation temperatures, and combinations thereof. In other words, the hydrogen carriers have the ability to store hydrogen and release hydrogen on demand.

[0144] The temperature (°C) for the dehydrogenation of saturated hydrocarbons may be in the range of about 20 to 700. For example, the temperature (°C) may be at least about 20, 50, 80, 100, 150, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 46, 480, 500, 520, 540, 560, 580, 600, 620, 640, 660, 680, or 700. For example, the temperature (°C) may be less than about 700, 680, 660, 640, 620, 600, 580, 560, 540, 520, 500, 480, 460, 440, 420, 400, 380, 360, 340, 330, 320, 300, 280, 260, 240, 220, 200, 150, 100, 80, 50, or 20. The temperature may also be provided at about any of these values or in a range between any of these values.

[0145] The pressure (bar) for the dehydrogenation of saturated hydrocarbons may be in the range of about 0 to 100, 5 to 80, 10 to 50 or 15 to 30. For example, the pressure

(bar) may be at least about 0, 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95 or 100. For example, the pressure (bar) may be less than about 100, 95, 90, 85, 80, 75, 70, 65, 60, 55, 50, 40, 30, 20, 15, 10, 5, 1, or 0. The pressure (bar) may be provided at about any of these values or in a range between any of these values, such as a range between about 1 to 80 or about 2 to 50. It will be appreciated that dehydrogenation reactions are performed at low pressure (in bar) and it is preferred to have no back pressure in the system.

Hydrogenation reactions

[0146] The hydrogenations using hydrogen gas or transfer hydrogenations using a liquid hydrogen donor may be for hydrogenating compounds containing one or more functional groups selected from one or more of alkenes, alkynes, aldehydes, carbonyls, ketones, carboxylic acids, ethers, esters, halides, imines, amides, nitrogen, nitriles and nitro groups. It will be appreciated that hydrogenation reactions may also include those that are used in chemical manufacture and hydrogenations that are used to re-hydrogenate spent dehydrogenated carriers, such as that described herein. It will also be appreciated that hydrogenation reactions may also include those for synthesizing hydrogen carriers such as ammonia and hydrogen peroxide.

[0147] In an embodiment, the functional groups selected from one or more of alkenes, alkynes, aldehydes, carbonyls, ketones, carboxylic acids, ethers, esters, halides, imines, amides, nitrogen, nitriles and nitro groups may be hydrogenated as follows: alkenes to alkanes, alkynes to alkenes and/or alkanes, aldehydes to alcohols, carbonyls to alcohols, ketones to alcohols, carboxylic acids to alcohols, ethers to alcohols, esters to alcohols, halides to hydrogen, imines to amines, amides to amines and alcohols, nitrogen to ammonia, nitriles to amines, and nitro groups to hydrogen, amine and/or anilines.

[0148] In an embodiment, the hydrogenation may also be for hydrogenating compounds to remove various protecting groups comprising any one or more of the above mentioned functional groups, such as protected ethers (e.g. benzyl or silyl protected ethers, see Green et al, Protective Groups in Organic Synthesis, Wiley-Interscience, New York, 1999).

[0149] The temperature (°C) for the hydrogenation of compounds containing one or more functional groups selected from one or more of alkenes, alkynes, aldehydes, carbonyls, ketones, carboxylic acids, ethers, esters, imines, amides, nitrogen, nitriles and nitro groups may be in the range of about 10 to 300. For example, the temperature (°C) may be at least about 10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, or 300. For example, the temperature (°C) may be less than about 300, 280, 260, 240, 220, 200, 190, 180, 170, 160, 150, 140, 100, 50, 40, 30, or 20. The temperature may also be provided at about any of these values or in a range between any of these values, such as a range between about 20 to 300°C, about 50 to 200°C, or about 100 to 180°C.

[0150] The pressure (bar) for the hydrogenation of compounds containing one or more function groups selected from one or more of alkenes, alkynes, aldehydes, carbonyls, ketones, carboxylic acids, ethers, esters, halides, imines, amides, nitrogen, nitriles and nitro groups may be in the range of about 1 to 100. For example, the pressure (bar) may be at least about 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, or 100. For example, the pressure (bar) may be less than about 100, 95, 90, 85, 80, 75, 70, 65, 60, 55, 50, 40, 30, 20, 15, 10 or 5. The pressure (bar) may also be provided at about any of these values or in a range between any of these values, such as a range between about 5 to 50 or about 10 to 25.

EXAMPLES

[0151] The present disclosure is further described by the following examples. It is to be understood that the following description is for the purpose of describing particular embodiments only and is not intended to be limiting with respect to the above description.

Example 1: Preparation of a catalyst composition

[0152] A stock slurry for the catalyst coating was prepared by addition of the catalyst (for instance, Pt/Al₂O₃ for LOHC dehydrogenation or Ru/Al₂O₃ for ammonia cracking) in deionised water (DI)). To increase the adhesion, a binder was used. The desired amount of the binder was added to a known amount of DI water and rotated on the roller for 2 days or until formation of a homogenous slurry was observed. Following

formation of the binder solution, the catalyst slurry was added to form a Binder/Catalyst coating slurry. Lower amounts of binder can be used depending on the catalyst and the static mixer.

Example 2: Coating method

[0153] Prior to coating a static mixer with a catalyst, the static mixer can be optionally pre-treated using dilute HCl, washed with water followed by acetone and then dried at 120°C for 2 hrs.

[0154] The static mixer was soaked in the prepared Binder/Catalyst slurry for 15 min assisted by shaker or roller, then allowed to stand in a stream of N₂ to prevent the blockage followed by drying. The above process can be repeated to increase the desired catalyst quantity required.

Example 3: Compound static mixer and reactor assembly

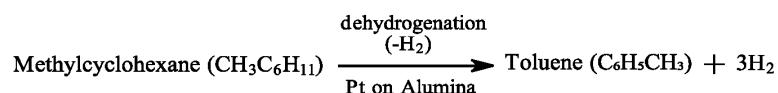
[0155] The experimental rig consists of a reactor module that houses the compound static mixer element (Figures 5 and 6). The reactor tube is made in stainless steel 316 (29 mm X 253 mm) with a socket weld flange welded at each end of the reactor tube. A spiral wound gasket (KLINGER Ltd. SWGAABABABG0002506) sandwiches between the welded flange and a blind flange to supply the system seal. The compound static mixer was coated with 6.4 g (~2 wt. % of total compound static mixer weight) of Pt on Al₂O₃ catalyst (5 wt. % loading powder from Sigma Aldrich) using dip coating method described above and further described in PCT/AU2020/050464.

[0156] The catalyst coated compound static mixer was inserted into the reactor assembly as shown in Figure 6. Metal tubes made in stainless steel 316 (Swagelok and Prochem, 1/4" OD tubes) were used to bring the liquid substrate feed from a dual syringe reagent pump (Teledyne ISCO 100DX Series), the gas feed line for N₂ supply, and to carry the output from the reactor into a collection vessel (Schott Bottle, 2L) for further analysis. A Nanodac™ Recorder/Controller was used to control the system temperature through an electric heat rod (10.13mm X 300mm, HotCo) located at the core of the compound static mixer. The pressure inside the reactor was regulated by a diaphragm back pressure regulator (BPR, Swagelok KBP1J0A4A5A20000) located at the outlet of

the reactor after the chiller unit where the hot effluent could optionally be cooled. The chiller unit consisted of a chamber with a metal coil (Prochem, ss 316, 1/4" OD) as the heat exchanger immersed in 50% glycol solution as the cooling fluid. The temperature of the chiller unit was controlled using a Julabo Thermostat (CD-200F, John Morris). Further safety components and monitoring equipment was installed in the rig: a safety pressure relief valve at the reactor inlet (Swagelok, SS-4R3A-KZ) and pressure transducers (Gems, GM-3100BE-100) at the reactor inlet (Pin) and after the cooling unit (Pout). Several thermocouples (TCs) were used to monitor the system temperature: three PT-100s to monitor the fluid stream inside the reactor after each pass; and K-type TCs for monitoring the fluid when it exited the reactor tube, on the outer reactor body around the centre of the reactor length and at its edge, at the gasket between the flanges, and at the tip of the heat rod. The thermal data was logged using digital loggers. The system set-up is shown in Figure 7. The reactor module can be dismantled easily in order to facilitate change-over of the catalytic inserts. The reaction occurred at the solid-liquid interface of the catalytic inserts, inside the reactor zone.

Example 4: Dehydrogenation reaction of methylcyclohexane (MCH)

[0157] The above-mentioned configuration/assembly was tailored for dehydrogenation reactions. To evaluate the reactor for dehydrogenation reactions, a series of experiments were conducted investigating the dehydrogenation of methyl cyclohexane (see Scheme 7).



Scheme 7. Dehydrogenation of Methylcyclohexane to Toluene using Pt/Al₂O₃ catalyst.

[0158] With minimal changes to the apparatus, the proposed reactor rig can be used for metal catalysed hydrogenation reactions, C-C coupling reactions, oxidations, or other organic reactions.

[0159] A typical dehydrogenation reaction on the above reactor configuration was conducted as follows:

[0160] Before the production run, the reactor was flushed with nitrogen gas ($\Delta P = 1$ bar) and the chiller temperature is set to $-20\text{ }^{\circ}\text{C}$ using the Julabo chiller to prepare the cooling unit. The reactor was then switched from N_2 gas to the reagent methylcyclohexane (ReagentPlus®, 99%) at the desired flow rate using the syringe pumps described above. The system pressure was set to the desired value using the diaphragm BPR to 5 bar under methylcyclohexane flow and the pressure was allowed to stabilise for several minutes. The reaction started once heating commenced and the system temperature was set to the desired value (TC0) using the Nanodac™ Recorder/Controller with TC0 as control. Over the course of temperature build up and stabilisation to the set value, several fractions of the feed were collected at the outlet and analysed. Reaction conversions were calculated from $^1\text{H-NMR}$ spectra which were recorded on a Bruker AC-400 spectrometer. Reaction conditions for the series of experiments are shown in Table 1.

Table 1: Control temperature, pressure, MCH feed rate, and conversions for a fixed catalyst amount.

Catalyst	Run	Control Temperature (TC ₀) $^{\circ}\text{C}$	Pressure (bar)	MCH Feed rate ($\text{mL}\cdot\text{min}^{-1}$)	Conversion %
Pt/Al₂O₃ (5 wt.%)	1	220	5	1.4	5.6
	2	250	5	1.4	7.8
	3	275	5	1.4	9.3
	4	300	5	1.4	14
	5	330	5	1.4	19.6
	6	330	0	1.4	10
	7	330	5	1.0	21.3
	8	330	5	1.8	17.5
	9	330	5	2.8	15.6
	10	360	5	1.4	25

[0161] In each of experiment, conversion of methylcyclohexane to toluene was observed. Conversion increased with the system temperature set point (TC0) as shown in Figure 8. A conversion up to 25% at steady state was observed for the maximum process temperature tested which is $360\text{ }^{\circ}\text{C}$ at $p = 5$ bar and MCH feed rate of $2.33 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$. Conversion also increases with increasing reaction time and decreasing MCH liquid hourly space velocity (LHSV) as shown in Figure 9.

Example 5: Ammonia cracking

[0162] Ammonia cracking experiments were performed using gas mixture containing 5% ammonia in nitrogen balance and a compound static mixer, as described above in Example 1 and 2.

[0163] A typical ammonia cracking experiment is described as follows. Before the production run, the reactor was flushed with nitrogen gas ($Q = 1 \text{ L.min}^{-1}$) for at least 20 minutes to create an inert atmosphere before introducing the ammonia gas mixture. The reactor was then switched from N_2 gas to the ammonia feed (5%) at the desired flow rate. The reaction started once heating commenced and the system temperature was set to the desired value. Over the course of temperature build up and stabilisation to the set value, the product gas was continuously analysed for residual ammonia levels on a microGC. Reaction conversions were calculated from the remainder ammonia levels as indicated by the GC spectra.

CLAIMS:

1. A compound static mixer element comprising:
at least a first fluidic chamber comprising a plurality of axially spaced flow directing panels each concentrically extending radially outward to the periphery and coaxially along the longitudinal axis of the first fluidic chamber to define a plurality of separate flow channels,
wherein each flow channel extends along the longitudinal axis of the first fluidic chamber and is configured at or near one opposing end for fluidic connection with an adjacent flow channel such that, in use, one or more fluidic reactants entering the first fluidic chamber into a first flow channel flow in a serpentine direction through the plurality of adjacent separate flow channels such that the one or more fluidic reactants flow through each separate flow channel consecutively, and
wherein each flow channel comprises a patterned porous scaffold defining a plurality of passages configured for mixing one or more fluidic reactants during flow and reaction thereof through the patterned porous scaffold such that the patterned porous scaffold links the plurality of flow directing panels.
2. The compound static mixer element of claim 1, comprising between 2 and 10 axially spaced flow directing panels defining between 2 and 10 separate flow channels respectively.
3. The compound static mixer element of claim 1, comprising 6 axially spaced flow directing panels defining 6 separate flow channels respectively.
4. The compound static mixer element of any one of claims 1 to 3, further comprising an inner second heat cavity chamber concentrically positioned with respect to the first chamber.
5. The compound static mixer element of claim 4, wherein the second heat cavity chamber is an inner hollow chamber configured to optionally support a heat exchanger.

6. The compound static mixer element of any one of the preceding claims, wherein at least 75% of each flow channel comprises the patterned porous scaffold defining a plurality of passages configured for mixing one or more fluidic reactants during flow and reaction thereof.
7. The compound static mixer element of any one of the preceding claims, wherein the patterned porous scaffold is a repetitive design of porous segments repeated periodically along the longitudinal axis of the first fluidic chamber to form a continuous lattice of interconnected segments configured for facilitating mixing of reactants and heat transfer.
8. The compound static mixer element of claim 7, wherein each segment comprises a plurality of passages defined by a plurality of interlinked polygonal prisms interconnected with bridging supports.
9. The compound static mixer element of any one of the preceding claims, wherein each flow channel is in fluid communication with an adjacent flow channel via an indent in each separating panel, wherein the indent is at or near opposing ends of each adjacent separating panel to allow the one or more fluidic reactants to pass through each flow channel in a serpentine direction.
10. The compound static mixer element of any one of the preceding claims, wherein the mixer element is configured for insertion into a continuous flow chemical reactor chamber.
11. The compound static mixer element of any one of the preceding claims, wherein the aspect ratio (L/d) of the scaffold is in the range of about 1 to 5000.
12. The compound static mixer element of any one of the preceding claims, wherein the diameter of the first fluidic chamber is between about 15 mm to about 5000 mm.

13. The compound static mixer element of any one of claims 2 to 11, wherein the diameter of the second heat cavity chamber is between about 1 mm to about 2500 mm.
14. The compound static mixer of any one of the preceding claims, wherein the average pore size of the patterned porous scaffold is between about 0.1 mm to about 5 mm.
15. The compound static mixer element of any one of the preceding claims, wherein the compound static mixer element is formed by additive manufacturing.
16. The compound static mixer element of any one of the preceding claims, wherein the volume displacement % of the compound static mixer relative to a reactor chamber for containing the mixer is less than 50.
17. The compound static mixer of any one of the preceding claims, wherein at least a portion of a surface of the patterned scaffold comprises a catalytic material or a catalyst support material comprising the catalyst material on a support material for providing the surface with catalytically reactive sites to form a compound catalytic static mixer.
18. The compound catalytic static mixer element of claim 16, wherein the catalytically reactive sites are provided by at least one of: the scaffold being formed from the catalytic material; the catalyst material being intercalated, interspersed and/or embedded with at least part of the scaffold; and at least a part of the surface of the scaffold comprising a coating comprising the catalyst material or a catalyst support material comprising the catalyst material on a support material.
19. The compound catalytic static mixer element of claim 18, wherein the coating is an electrodeposition or dip coating.
20. The compound catalytic static mixer element of claim 18 or claim 19, the amount of catalyst material or catalyst support material on the surface of the scaffold is

in a range between about 0.5 wt.% and 10 wt.% based on the total weight % of the compound static mixer.

21. The compound catalytic static mixer element of claims 18 to 20, wherein the catalyst material or catalyst support material can be regenerated.

22. The compound catalytic static mixer element of any one of the preceding claims, wherein the scaffold comprises or consists of a metal, metal alloy, cermet and metal oxide.

23. The compound catalytic static mixer element of claim 22, wherein the scaffold comprises or consists of titanium, aluminium or stainless steel.

24. A process for releasing hydrogen from a hydrogen carrier comprising (i) introducing the hydrogen carrier into a continuous flow chemical reactor comprising a compound catalytic static mixer element; (ii) dehydrogenating the hydrogen carrier as it passes through the reactor whereby said dehydrogenating produces hydrogen and a dehydrogenated carrier; (iii)(a) obtaining an output stream comprising hydrogen and the dehydrogenated carrier; and (iv) separating hydrogen and the dehydrogenated carrier,

wherein the compound catalytic static mixer element is according to any one of claims 1 to 23.

25. The process of claim 24, wherein, in step (ii), the temperature of the hydrogen carrier is maintained between about 20°C and 1000°C while it passes through the static mixer element.

26. The process of claim 24 or claim 25, wherein step (iii)(a) further comprises step (iii)(b) wherein the output stream comprising hydrogen and the dehydrogenated carrier passes through a cooling system.

27. The process of any one of claims 24 to 26, wherein the process further comprises flushing the reactor with a stream of inert gas, preferably nitrogen (N₂) gas, prior to introducing the hydrogen carrier.
28. The process of any one of claims 24 to 27, wherein the process further comprises passing the hydrogen carrier through a first filter to remove particulates from the hydrogen carrier prior to step (i).
29. The process of any one of claims 24 to 28, wherein the process further comprises passing the dehydrogenated carrier through a second filter to remove catalyst material or catalyst support in the output stream prior to the dehydrogenated carrier passes through a cooling system in step (iii)(b).
30. The process of any one of claims 24 to 29, wherein a product conversion rate (% hydrogen carrier converted to dehydrogenated carrier) is at least 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 99, 99.5, or 99.9%.
31. The process of any one of claims 24 to 30, wherein the hydrogen is re-introduced into the continuous flow chemical reactor with a second fluidic reactant, wherein the second fluidic reactant is an organic compound capable of hydrogenation.
32. The process of any one of claims 24 to 31, wherein the hydrogen carrier is a liquid organic hydrogen carriers (LOHC), hydrogen peroxide or ammonia.
33. A process for synthesizing a product by hydrogenation reaction of at least a first fluidic reactant with a second fluidic reactant, the process comprising:
(i) introducing at least a first and second fluidic reactant, or source thereof, into a continuous flow chemical reactor comprising a compound catalytic static mixer element via the one or more reactant inlets; (ii) operating the reactor, or control means thereof, to provide flow and hydrogenation reaction of the first and second fluidic reactant through the compound static mixer; and (iii) obtaining an output stream

comprising a product of a hydrogenation reaction of at least the first and second fluidic reactants,

wherein the compound catalytic static mixer element is according to any one of claims 1 to 23.

34. The process of claim 33, wherein the at least first fluid reactant is hydrogen gas (molecular hydrogen) or a liquid hydrogen donor.

35. The process of claim 33 or claim 34, wherein the at least second fluidic reactant is an organic compound capable of hydrogenation.

36. The process of claim 33 or claim 34, wherein the at least second fluidic reactant is an oxygen gas or nitrogen gas.

37. The process of any one of claims 33 to 36, wherein, in step (ii), the temperature of the first and second fluid reactants is maintained between about 10°C and 300°C while it passes through the static mixer element.

38. The process of any one of claims 24 to 37, wherein the mean residence time in the compound static mixer or reactor is in a range of about 1 second to about 5 hours.

39. The process of any one of claims 24 to 38, wherein the pressure (bar) is in the range of about 1 to 100.

40. A continuous flow chemical reactor for use in reaction of one or more fluidic reactants, the reactor comprising:

the compound static mixer element of claims 1 to 16 or compound catalytic static mixer element of any one of claims 17 to 23;

a reactor chamber configured for receiving and housing the compound static mixer element;

at least one reactant inlet for supply of the one or more fluidic reactants to the reactor chamber section; and

at least one outlet in fluidic communication with the static mixer for receiving an output stream comprising a product of the reaction,

wherein the inlet and outlet is separated by the static mixer element, and

wherein the static mixer element disposed within the reactor chamber is configured for dispersing and mixing the one or more fluidic reactants during flow and reaction thereof through the mixer.

41. The continuous flow chemical reactor of claim 40, wherein the reactor comprises at least one heat exchanger system to allow control of the temperature of the reactor, compound static mixer element, or fluidic components thereof.

42. The continuous flow chemical reactor of claim 40 or claim 41, wherein the heat exchanger system comprises a controller to control the temperature of the reactor, static mixer element, or fluidic components thereof.

43. The continuous flow chemical reactor of claim 42, wherein the heat exchanger system comprises a shell, tube, or rod heat exchanger.

44. The continuous flow chemical reactor of any one of claims 40 to 43, wherein the reactor is a tubular reactor.

45. The continuous flow chemical reactor of any one of claims 40 to 44, wherein the reactor further comprises at least one flange, at least one gasket, and at least one blind flange to seal the reactor, wherein the at least one gasket is fitted in between the at least one flange and at least one blind flange.

46. A system for providing a continuous flow chemical reaction comprising:
a continuous flow chemical reactor comprising a compound static mixer according to any one of claims 1 to 23 or a continuous flow chemical reactor according to any one of claims 40 to 45;

a pump for providing fluidic flow for one or more fluidic reactants and any products thereof through the reactor;

one or more heat exchangers to allow for control of the temperature of the reactor, reactor chamber section, static mixer element, or fluidic components thereof; and

a controller for controlling one or more of the parameters of the system selected from concentration, flow rate, temperature, pressure, and residence time, of the one or more fluidic reactants, or sources or products thereof.

47. The system of claim 46, wherein the system further comprises a cooling system for cooling the output stream comprising a product of the reaction.

48. The system of claim 46 or claim 47, wherein the system comprises at least one filter to remove particulates from the one or more fluidic reactants prior to the reactant inlet and/or to remove catalyst material or catalyst support in the output stream comprising a product of the reaction.

49. The system of any one of claims 46 to 48, wherein the system further comprises at least one membrane for separation of products.

50. The continuous flow chemical reactor of claims 40 to 45 or system of claims 46 to 49, wherein the reaction is dehydrogenation and/or hydrogenation.