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(54) Title: REACTOR AND METHOD OF USING SAME

FIG. 1

(57) Abstract: A reactor is disclosed that is configured to provide for a flow of reactant material in one direction and a flow of a coolant material in a direction perpendicular to the flow of reactant material.
REACTOR AND METHOD OF USING SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This Application claims the benefit of U.S. Provisional Application No. 62/259,756, filed November 25, 2015, which is incorporated herein by reference in its entirety.

FIELD

[0002] This invention relates to a reactor for performing chemical reactions to produce desired reaction products and, more particularly, to reactors for providing robust control of chemical reaction parameters.

BACKGROUND

[0003] Exothermic chemical reactions produce in part energy, in the form of heat. Exothermic chemical reactions are often driven by a catalyst, such as a metallic catalyst. During an exothermic chemical reaction, if the produced heat is not removed continuously, the metallic catalyst can be damaged, runaway can occur and the products generated will start to deviate from the desired range and thereby cause problems for downstream processing.

[0004] Accordingly, there is a need in the art for reactors that provide more efficient control over reaction parameters while also providing continuous heat removal.

SUMMARY

[0005] Disclosed herein is a reactor comprising for producing reaction products, the reactor having a feed axis, a first transverse axis perpendicular to the feed axis, and a second transverse axis perpendicular to the feed axis and the first transverse axis, the reactor comprising: a housing having an outer wall surrounding the feed axis of the reactor; at least one catalyst bed positioned within the housing, wherein the least one catalyst bed catalyst bed is configured to receive one or more catalyst materials; and a plurality of coolant conduits positioned within the housing, wherein each of the at least one catalyst bed and the plurality of coolant conduits are spaced apart relative to the first transverse axis, each coolant conduit having a longitudinal axis oriented substantially parallel to the second transverse axis of the reactor and being configured to receive one or more coolant materials, and permit flow of the one or more coolant materials relative to the second transverse axis, wherein the plurality of coolant conduits are positioned in thermal communication with the at least one catalyst bed,
and wherein each catalyst bed of the at least one catalyst bed is configured to receive one or more reactant materials flowing relative to the feed axis.

[0006] Also disclosed herein is a method of performing a chemical reaction in a reactor disclosed herein.

[0007] Additional advantages of the invention will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The advantages of the invention will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

DETAILED DESCRIPTION OF THE FIGURES

[0008] These and other features of the preferred embodiments of the invention will become more apparent in the detailed description in which reference is made to the appended drawings wherein:

[0009] FIG. 1 is a front cross-sectional perspective view of an exemplary reactor as disclosed herein.

[0010] FIG. 2 is an end cross-sectional side perspective view of another exemplary reactor as disclosed herein.

DETAILED DESCRIPTION

[0011] The present invention can be understood more readily by reference to the following detailed description, examples, drawings, and claims, and their previous and following description. However, before the present devices, systems, and/or methods are disclosed and described, it is to be understood that this invention is not limited to the specific devices, systems, and/or methods disclosed unless otherwise specified, as such can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting.

[0012] The following description of the invention is provided as an enabling teaching of the invention in its best, currently known embodiment. To this end, those skilled in the relevant art will recognize and appreciate that many changes can be made to the various aspects of the invention described herein, while still obtaining the beneficial results of the present invention. It will also be apparent that some of the desired benefits of the present
invention can be obtained by selecting some of the features of the present invention without utilizing other features. Accordingly, those who work in the art will recognize that many modifications and adaptations to the present invention are possible and can even be desirable in certain circumstances and are a part of the present invention. Thus, the following description is provided as illustrative of the principles of the present invention and not in limitation thereof.

[0013] Before the present compounds, compositions, articles, systems, devices, and/or methods are disclosed and described, it is to be understood that they are not limited to specific synthetic methods unless otherwise specified, or to particular reagents unless otherwise specified, as such can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting. Although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, example methods and materials are now described.

[0014] All publications mentioned herein are incorporated herein by reference to disclose and describe the methods and/or materials in connection with which the publications are cited.

[0015] As used throughout, the singular forms "a," "an" and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "an outlet opening" can include two or more such outlet openings unless the context indicates otherwise.

[0001] Ranges can be expressed herein as from "about" one particular value, and/or to "about" another particular value. When such a range is expressed, another aspect includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another aspect. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint. It is also understood that there are a number of values disclosed herein, and that each value is also herein disclosed as "about" that particular value in addition to the value itself. For example, if the value "10" is disclosed, then "about 10" is also disclosed. It is also understood that each unit between two particular units are also disclosed. For example, if 10 and 15 are disclosed, then 11, 12, 13, and 14 are also disclosed.
[0002] The terms "first," "first transverse axis," "second," "second transverse," and the like, where used herein, do not denote any order, quantity, or importance, and are used to distinguish one element from another, unless specifically stated otherwise.

[0016] As used herein, the terms "optional" or "optionally" mean that the subsequently described event or circumstance may or may not occur, and that the description includes instances where said event or circumstance occurs and instances where it does not.

[0017] The word "or" as used herein means any one member of a particular list and also includes any combination of members of that list.

[0018] Moreover, it is to be understood that unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not actually recite an order to be followed by its steps or it is not otherwise specifically stated in the claims or descriptions that the steps are to be limited to a specific order, it is no way intended that an order be inferred, in any respect. This holds for any possible non-express basis for interpretation, including: matters of logic with respect to arrangement of steps or operational flow; plain meaning derived from grammatical organization or punctuation; and the number or type of aspects described in the specification.

[0019] Described herein, in various aspects, is a reactor for performing chemical reactions to produce one or more desired reaction products. In operation, it is contemplated that the reactors can provide robust temperature control for chemical reactions while also providing feed composition adjustment flexibility. It is further contemplated that the reactors can provide superior operational control to thereby optimize the distribution and/or quality of the reaction products. As further described below, it is contemplated that the reactors disclosed herein can achieve more uniform cooling flow and more uniform cooling than conventional reactor designs. It is further contemplated that the reactors disclosed herein can be configured to maintain partial pressures within a reactant feed to thereby keep reactant ratios substantially constant. It is still further contemplated that the reactants can define distinct stages with coolant entrances and exits to provide for better coolant control within the reactor.

1. REACTOR WITH CATALYST BED AND COOLANT CONDUIT

[0020] Disclosed herein is a reactor that is capable to support processes for performing exothermic reactions. The exothermic reactions can be gas-solid type exothermic reactions,
liquid-solid exothermic reactions, and/or gas-liquid-solid exothermic reaction. In most gas-solid exothermic reactions, such as a CO hydrogenation reaction that produces hydrocarbons and oxygenates, heat removal from the catalyst best and mass transfer diffusion limitation are parameters that needs to be controlled to achieve desired products and yields. Similarly, in etherification reactions, such as a reaction that produces methyl tertiary butyl ether (MTBE), heat removal is a parameter that significantly impacts the productivity per unit volume of the catalyst. The reactor disclosed herein is capable of having a high heat removal capability, which increases the efficacy of an exothermic reaction in the reactor.

[0021] Disclosed herein is a reactor comprising for producing reaction products, the reactor having a feed axis, a first transverse axis perpendicular to the feed axis, and a second transverse axis perpendicular to the feed axis and the first transverse axis, the reactor comprising: a housing having an outer wall surrounding the feed axis of the reactor; at least one catalyst bed positioned within the housing, wherein the least one catalyst bed catalyst bed is configured to receive one or more catalyst materials; and a plurality of coolant conduits positioned within the housing, wherein each of the at least one catalyst bed and the plurality of coolant conduits are spaced apart relative to the first transverse axis, each coolant conduit having a longitudinal axis oriented substantially parallel to the second transverse axis of the reactor and being configured to receive one or more coolant materials, and permit flow of the one or more coolant materials relative to the second transverse axis, wherein the plurality of coolant conduits are positioned in thermal communication with the at least one catalyst bed, and wherein each catalyst bed of the at least one catalyst bed is configured to receive one or more reactant materials flowing relative to the feed axis. Accordingly, the reactor is configured to allow for the flow of reactants to be perpendicular to the flow of coolant during use. Such a configuration in a reactor provides for improved control of heat removal from catalyst bed, where the exothermic reaction is performed.

[0022] In one aspect, the plurality of coolant conduits is a plurality of plate type coolant conduits.

[0023] In one aspect, the reactor further comprises one or more reactant inlets, wherein each of the one or more reactant inlets allows flow of a reactant material relative to the feed axis of the reactor; and one or more product outlets, wherein the at least one catalyst bed is positioned between the one or more reactant inlets and the one or more reactant outlets relative to the feed axis. The one or more reactant inlets can be located to promote uniform distribution of the reactants material over the at least one catalyst bed. The at least one
catalyst bed can comprise multiple catalyst beds positioned relative to the first transverse axis within the housing. For example, the multiple catalyst beds can be positioned from one end of the reactor to the other end of the reactor relative to the first transverse axis. Accordingly, it desired that the multiple catalyst beds receive a similar amount of reactant material for conversion to desired products.

[0024] In one aspect, the reactor further comprises one or more temperature sensors positioned within the housing. In one aspect, the one or more temperature sensors are located within the housing in a space between the outer wall of the housing and the least one catalyst bed.

[0025] The one or more temperature sensors can comprise a thermometer, such as a digital thermometer. The reactor can comprise two, three, four, five, six, or seven temperature sensors positioned within the housing. When the reactor comprises more than one temperature sensors, they can be positioned at multiple locations within the housing. Such an arrangement of the temperature sensors can be used to determine the temperature at multiple locations within the reactor. Each temperature sensor within the reactor can be monitored individually. The flow of reactant material and/or coolant can be determined based on the temperature in the reactor. For example, if the temperature is higher than desired, then the flow of reactant material can be decreased and/or the flow of coolant can be increased.

[0026] Suitable coolants include, but are not limited to boiler feed water (BFW), steam, water, a molten salt, a synthetic liquid, an oil and an ionic liquid, or a combination thereof. In one aspect, the coolant can comprise BFW. In another aspect, the coolant can comprise steam. In yet another aspect, the coolant can comprise BFW and steam. In yet another aspect, the coolant can comprise water. In yet another aspect, the coolant can comprise a molten salt, such as for example, a molten salt comprising LiF, BeF₂, NaF, ZrF₄, or KF, or combinations thereof. In yet another aspect, the coolant can comprise a synthetic liquid. In yet another aspect, the coolant can comprise an oil. In yet another aspect, the coolant can comprise an ionic liquid, such as an ionic liquid comprising an anion selected from the group consisting of diethylphosphate, triphenylphosphate, methansulfonate, trifluormethansulfonate, methylsulfate, ethylsulfate, SiF₆²⁻, tetrachloroferrat-(III) and tetrafluoroborate, and a cation selected from the group consisting of ammonium, phosphonium, pyridinium, pyrrolium, piperidinium, pyrrolidinium, morpholinium, (benz)imidazolium, and pyrazolium.
[0027] In one aspect, the reactor further comprises one or more thermowells, wherein the one or more thermowells at least partially surrounds the one or more temperature sensors. For example, the one or more thermowells can fully surrounds the one or more temperature sensors. The one or more thermowells protect the one or more temperature sensors from being damaged within the reactor. The one or more thermowells are made of a thermally conductive material that allows heat transfer from the housing to the one or more temperature sensors.

[0028] In one aspect, each of the at least one catalyst bed has a longitudinal axis oriented substantially parallel to the feed axis of the reactor.

[0029] In one aspect, the one or more catalyst beds are positioned on one or more catalyst bed supports. The catalyst bed support can be made of a non-reactive material with a high mechanical strength and thermal resistance. Suitable materials include, but are not limited to, alumina and ceramic.

[0030] In one aspect, the plurality of coolant conduits comprises a plurality of plates arranged to define the plurality of coolant conduits, wherein the plurality of plates arranged have a longitudinal axis substantially parallel to the second transverse axis. In one aspect, the plurality of coolant conduits and the one or more catalysts bed are arranged in alternating order relative to the first transverse axis. For example, a coolant conduit can be directly next to a catalyst bed that is directly next to another coolant conduit that is directly next to another catalyst bed, and so on.

[0031] In one aspect, the plurality of plates is adjustable in a direction substantially parallel to the first transverse axis. Thus, the plates can be adjusted to increase or decrease the volume of a coolant conduit. The volume of a coolant conduit can determine the amount and flow of coolant, which in turn influences the cooling rate of the one or more catalyst beds.

[0032] In one aspect, each of the plurality of coolant conduits has a width of from about 1 mm to about 100 mm. For example, each of the plurality of coolant conduits has a width of from about 10 mm to about 100 mm, from about 25 mm to about 100 mm, and from about 50 mm to about 100 mm.

[0033] In one aspect, the reactor comprises from 2 to about 10,000 catalyst conduits. For example, the reactor can comprise from 1,000 to 10,000 catalyst conduits.

[0034] In one aspect, the reactor comprises from 2 to about 10,000 catalyst beds. For
example, the reactor can comprise from 1,000 to 10,000 catalyst beds.

[0035] In one aspect, the each of the one or more reactant inlets is in communication with a reactant distributor for distributing reactant material uniformly over the one or more catalyst beds.

[0036] In one aspect, the reactor further comprises one or more coolant inlets that are in communication with the plurality of coolant conduits and is configured to transport coolant through the reactor in a direction relative to the second transverse axis. In one aspect, the reactor can further comprise a coolant collection area positioned in communication with both the one or more coolant inlets and the plurality of coolant conduits. The coolant enters the coolant collection area from the one or more coolant inlets. The coolant then enters the plurality of coolant conduits.

[0037] In one aspect, the reactor comprises two or more reactant inlets. For example, the reactor can comprise two, three, four, five or six reactant inlets. Each of the two or more reactant inlets can be in communication with a reactant distributor. Reactant distributors are known in the art.

[0038] In one aspect, the plurality of the coolant conduits is not tubular in shape. For example, the plurality of coolant conduits are defined by rectangular plates.

[0039] In one aspect, the reactor further comprises a means for adjusting the temperature of the catalyst bed, such as a cooling element or a heating element. For example, the reactor can further comprise a heating element that can increase the temperature of the catalyst bed. In another example, the reactor can further comprise means for adjusting the flow of reactant material, which can decrease or increase the temperature of the catalyst bed. In another example, the reactor can further comprise means for adjusting the flow of coolant, which can decrease or increase the temperature of the catalyst bed. In another example, altering the temperature of the reactant materials (feed pre-heating) can be used to control the catalyst bed temperature.

[0040] In one aspect, the at least one catalyst bed further comprises a heating element or a cooling element or both. For example, the at least one catalyst bed can further comprises a heating element. In another example, the at least one catalyst bed can further comprises a cooling element. In yet another example, the at least one catalyst bed can further comprises a heating element and a cooling element.

[0041] In one aspect, the plurality of coolant conduits are positioned within the housing
to define a space between the plurality of coolant conduits and the outer wall of the housing in a direction parallel to the second transverse axis.

[0003] In one aspect, the reactor is an industrial sized reactor. The reactor disclosed herein can have a volume of at least about 1,000 liters, about 2,000 liters, about 5,000 liters, or about 20,000 liters. For example, the reactor can have a volume from about 1,000 liter to about 20,000 liters.

[0042] Also disclosed herein is a reactor system comprising two or more of the reactors disclosed herein.

[0043] In one aspect, the two or more of the reactors are arranged in a series configuration.

[0044] In one aspect, the two or more of the reactors are arranged in a parallel configuration.

[0045] Methods of using the described reactor to perform a chemical reaction, such as a chemical exothermic reaction, are also disclosed. In one aspect, the described reactors can be used to perform a method comprising performing an exothermic chemical reaction selected from the group consisting of a gas-solid type exothermic reactions, liquid-solid exothermic reactions, gas-liquid-solid exothermic reaction, such as for example, a CO hydrogenation reaction or an etherification reaction, such as for example a reaction that produces MTBE.

[0046] In operation, the reactor can provide robust temperature control for chemical exothermic reactions while also providing feed composition adjustment flexibility. The reactor can also provide superior operational control to thereby optimize the distribution and/or quality of the reaction products. As further described herein, the reactors can: achieve more uniform cooling flow and more uniform cooling than conventional reactor designs; provide temperature control; maintain partial pressures within a reactant feed to thereby keep reactant ratios substantially constant; and define coolant flow perpendicular to reactant flow to provide for better coolant control within the reactor.

[0047] Described herein with reference to FIG. 1 and 2 is a reactor 1 for producing one or more desired reaction products. The reactor has a feed axis 15. The reactor also has a first transverse axis 16 that is perpendicular to the feed axis 15, see FIG. 1. The reactor also has a second transverse axis 17 that is perpendicular to the first transverse axis 16 and to the feed axis 15, see FIG. 2. In exemplary aspects, the reactor 1 can comprise a housing 18 having an
outer wall surrounding the feed axis 15. The reactor 1 also has at least one catalyst bed 7 positioned within the housing 18. The least one catalyst bed catalyst bed 7 is configured to receive one or more catalyst materials from one or more reactant inlets 3. Each of the one or more reactant inlets 3 can be in communication with a reactant distributor 12 that is configured to distribute reactant material uniformly over the at least one catalyst bed 7 and 9. The reactor 1 also has a plurality of coolant conduits 2 positioned within the housing 18. One or more coolant materials are transported from one or more coolant inlets 4 to a coolant material storage area 13, which is a space in the reactor between the plurality of coolant conduits 2 and the one or more coolant inlets 4 (and the outer wall of the housing 18). Each coolant conduit has a longitudinal axis oriented substantially parallel to the second transverse axis 17 of the reactor 1 and being configured to receive one or more coolant materials from the one or more reactor inlets 4. Such an orientation permit flow of the one or more coolant materials relative to the second transverse axis from the one or more reactor inlets 4 to the plurality of coolant conduits 2. The coolant material then exits the reactor 1 via one or more coolant outlets 10. In one aspect, there can be a space 14 between the plurality of coolant conduits 2 and the one or more coolant outlets 10. Each of the at least one catalyst bed 7 and the plurality of coolant conduits 2 are spaced apart relative to the first transverse axis 16. Furthermore, the plurality of coolant conduits 2 are positioned in thermal communication with the at least one catalyst bed 7. Each catalyst bed 7 of the at least one catalyst bed 7 is configured to receive one or more reactant materials flowing relative to the feed axis 15. In these aspects, it is contemplated that the at least one of catalyst bed 7 can comprise from 2 to about 100 catalyst beds, depending upon the dimensions of the catalyst beds 7, the coolant conduits 2, and the housing 18. Similarly, it is contemplated that the plurality of coolant conduits 2 can comprise from 2 to about 10,000 coolant conduits, depending upon the dimensions of the coolant conduits 2, the catalyst conduits 7, and the housing 18. In exemplary aspects, it is contemplated that each respective catalyst conduit 7 can have a diameter (or maximum width through a center point of the conduit) ranging from about 1 mm to about 100 mm inches. Similarly, it is contemplated that each respective coolant conduit 2 can have a diameter (or maximum width through a center point of the conduit) ranging from about 1 mm to about 100 mm.

In one aspect, the reactor 1 can also have one or more product outlets 5. The one or more product outlets 5 are configured to receive products flowing in a direction relative to the feed axis 15. In the reactor 1, the at least one catalyst bed 7 and plurality of coolant
conduits 2 are positioned between the one or more reactant inlets 3 and the one or more product outlets 5 relative to the feed axis.

[0049] In one aspect, the reactor 1 has one or more catalyst bed supports 6. The one or more catalyst bed supports 6 are positioned to be in communication with the at least one catalyst bed 7. In the reactor 1, the at least one catalyst bed 7 and plurality of coolant conduits 2 are positioned between the one or more reactant inlets 3 and the one or more catalyst bed supports 6 relative to the feed axis.

[0050] In one aspect, one or more temperature sensors 11 are positioned within the housing 18. The one or more temperature sensors 11 are configured to monitor the temperature within the reactor 1, such as, the temperature with the one or more catalyst beds 7. The one or more temperature sensors 11 can be positioned within one or more thermowells that at least partially surrounds the one or more temperature sensors 11.

[0051] In one aspect, the reactor 1 is configured to have a cavity 8 defined by the at least one catalyst bed 7 and plurality of coolant conduits 2 and the outer wall of the housing where products and unreacted reactant material can be collected after the reactant material has passed through the at least one catalyst bed 7 relative to the feed axis. The products and unreacted reactant material can be collected can be collected in this cavity 8 prior to exiting the reactor 1 via the one or more product outlets 5.

[0052] In another aspect, it is contemplated that each catalyst bed 7 can be configured to receive one or more catalyst materials. In exemplary aspects, each catalyst bed 7 can be substantially tubular or have a substantially rectangular (e.g., square) cross-sectional profile. More generally, it is contemplated that each catalyst bed 7 can have any desired cross-sectional profile.

[0053] In a further aspect, it is contemplated that each coolant conduit 2 can be configured to receive one or more coolant materials. In exemplary aspects, each coolant conduit 7 can be substantially tubular or can have a substantially rectangular (e.g., square) cross-sectional profile. More generally, it is contemplated that each coolant conduit 2 can have any desired cross-sectional profile.

[0054] In exemplary aspects, the plurality of coolant conduits 2 can be interspersed among the plurality of catalyst beds 7. In these aspects, it is contemplated that each catalyst bed 7 can be positioned adjacent to at least two coolant conduits 2 of the plurality of coolant conduits. In these aspects, and as further disclosed herein, it is contemplated that the plurality
of coolant conduits 2 can provide indirect cooling to the at least one catalyst bed 7. In still further exemplary aspects, it is contemplated that the at least one catalyst bed 7 and the plurality of coolant conduits 2 can optionally be substantially equally distributed within the housing 18. In still further exemplary aspects, it is contemplated that the combined cross-sectional area of the at least one catalyst bed 7 can be substantially equivalent to the combined cross-sectional area of the plurality of coolant conduits 2. In operation, it is contemplated that the positioning of the coolant conduits 2 and the at least one catalyst bed 7 as disclosed herein can achieve more uniform cooling flow and more uniform cooling than conventional reactors.

2. METHODS OF USING THE REACTOR

[0055] In use, the disclosed reactors can be used to perform a chemical reaction, such as an exothermic reaction, to thereby produce one or more desired reaction products.

[0056] Accordingly, disclosed herein is a method comprising the step of: a) performing a chemical reaction in a reactor disclosed herein. In exemplary aspects, the chemical reaction can be selected from the group consisting of a gas-solid type exothermic reactions, liquid-solid exothermic reactions, and gas-liquid-solid exothermic reaction. In one aspect, the gas-solid exothermic reaction is a CO hydrogenation reaction. In one aspect, the gas-solid exothermic reaction is an etherification reaction, such as an etherification reaction that produces methyl tertiary butyl ether (MTBE).

[0057] In one aspect, the method comprises flowing reactant materials through at least one catalyst bed in a direction substantially parallel to the feed axis, and flowing coolant through the plurality of cooling conduits in a direction substantially parallel to the second transverse axis.

[0058] In one aspect, a method of performing the chemical exothermic reaction can comprise filling the plurality of coolant conduits with a coolant material selected from the group consisting of boiler feed water (BFW), steam, water, a molten salt, a synthetic liquid, an oil and an ionic liquid, or a combination thereof. In another aspect, the method can comprise positioning at least one catalyst material within the at least one catalyst bed. In this aspect, it is contemplated that the at least one catalyst material can comprise catalyst particles that are configured to form a fixed bed within a respective catalyst bed. In an additional aspect, the method can comprise delivering at least one reactant material to the one or more reactant inlets. Optionally, in a further aspect, at least one coolant conduit of the plurality of
coolant conduits is not filled with coolant material. In this aspect, it is contemplated that the
at least one coolant conduit that is not filled with coolant material can effectively create a
draft for low-temperature reactions.

[0059] In exemplary aspects, it is contemplated that the ratio of the total combined
surface area of the plurality of coolant conduits to the total combined surface area of catalyst
within the housing can be selectively adjustable. Thus, in exemplary aspects, it is
contemplated that the method can further comprise selectively adjusting the ratio of the total
combined surface area of catalyst to the total combined surface area of catalyst within the
housing. In these aspects, the method can comprise one or more of positioning additional
coolant materials within one or more coolant conduits, removing coolant material from one or
more coolant conduits, positioning additional catalyst within one or more catalyst conduits,
and removing catalyst from one or more catalyst conduits.

[0060] In one aspect, the method further comprises collecting a product.

3. ASPECTS

[0061] In view of the described reactor and methods and variations thereof, herein below
are described certain more particularly described aspects of the inventions. These
particularly recited aspects should not however be interpreted to have any limiting effect on
any different claims containing different or more general teachings described herein, or that
the "particular" aspects are somehow limited in some way other than the inherent meanings
of the language and formulas literally used therein.

[0062] Aspect 1: A reactor for producing reaction products, the reactor having a feed
axis, a first transverse axis perpendicular to the feed axis, and a second transverse axis
perpendicular to the feed axis and the first transverse axis, the reactor comprising: a housing
having an outer wall surrounding the feed axis of the reactor; at least one catalyst bed
positioned within the housing, wherein the least one catalyst bed catalyst bed is configured to
receive one or more catalyst materials; and a plurality of coolant conduits positioned within
the housing, wherein each of the at least one catalyst bed and the plurality of coolant conduits
are spaced apart relative to the first transverse axis, each coolant conduit having a
longitudinal axis oriented substantially parallel to the second transverse axis of the reactor
and being configured to receive one or more coolant materials, and permit flow of the one or
more coolant materials relative to the second transverse axis, wherein the plurality of coolant
conduits are positioned in thermal communication with the at least one catalyst bed, and
wherein each catalyst bed of the at least one catalyst bed is configured to receive one or more reactant materials flowing relative to the feed axis.

[0063] Aspect 2: The reactor of aspect 1, wherein the reactor further comprises one or more reactant inlets, wherein each of the one or more reactant inlets allows flow of a reactant material relative to the feed axis of the reactor; and one or more product outlets, wherein the at least one catalyst bed is positioned between the one or more reactant inlets and the one or more reactant outlets relative to the feed axis.

[0064] Aspect 3: The reactor of aspects 1 or 2, wherein the reactor further comprises one or more temperature sensors positioned within the housing.

[0065] Aspect 4: The reactor of aspect 3, wherein the reactor further comprises one or more thermowells, wherein the one or more thermowells at least partially surrounds the one or more temperature sensors.

[0066] Aspect 5: The reactor of aspects 3 or 4, wherein the one or more temperature sensors are located within the housing in a space between the outer wall of the housing and the least one catalyst bed.

[0067] Aspect 6: The reactor of any one of aspects 1-5, wherein each of the at least one catalyst bed has a longitudinal axis oriented substantially parallel to the feed axis of the reactor.

[0068] Aspect 7: The reactor of any one of aspects 1-6, wherein the one or more catalyst beds are positioned on one or more catalyst bed supports.

[0069] Aspect 8: The reactor of any one of aspects 1-7, wherein the plurality of coolant conduits comprises a plurality of plates arranged to define the plurality of coolant conduits, wherein the plurality of plates arranged have a longitudinal axis substantially parallel to the second transverse axis.

[0070] Aspect 9: The reactor of aspect 8, wherein the plurality of plates are adjustable in a direction substantially parallel to the first transverse axis.

[0071] Aspect 10: The reactor of any one of aspects 1-9, wherein each of the plurality of coolant conduits has a width of from about 1 mm to about 100 mm.

[0072] Aspect 11: The reactor of any one of aspects 2-10, wherein the each of the one or more reactant inlets is in communication with a reactant distributor for distributing reactant material uniformly over the one or more catalyst beds.
[0073] Aspect 12: The reactor of any one of aspects 2-11, wherein the reactor comprises two or more reactant inlets.

[0074] Aspect 13: The reactor of any one of aspects 1-12, wherein the plurality of the coolant conduits are not tubular in shape.

[0075] Aspect 14: The reactor of any one of aspects 1-13, wherein the reactor further comprises a means for adjusting the temperature of the catalyst bed.

[0076] Aspect 15: The reactor of any one of aspects 1-14, wherein the at least one catalyst bed further comprises a heating element or a cooling element or both.

[0077] Aspect 16: The reactor of any one of aspects 1-15, wherein the plurality of coolant conduits are positioned within the housing to define a space between the plurality of coolant conduits and the outer wall of the housing in a direction parallel to the second transverse axis.

[0078] Aspect 17: The reactor of any one of aspects 1-16, the reactor further comprises one or more coolant inlets that are in communication with the plurality of coolant conduits and is configured to transport coolant through the reactor in a direction relative to the second transverse axis.

[0079] Aspect 18: The reactor of any one of aspects 1-16, wherein the reactor is an industrial sized reactor.

[0080] Aspect 19: A reactor system comprising two or more of the reactors of any one of aspects 1-18.

[0081] Aspect 20: The reactor system of aspect 19, wherein the two or more of the reactors are arranged in a series configuration.

[0082] Aspect 21: The reactor system of aspect 20, wherein the two or more of the reactors are arranged in a parallel configuration.


[0084] Aspect 23: The method of aspect 22, wherein the chemical reaction is an exothermic chemical reaction.

[0085] Aspect 24: The method aspects 22 or 23, wherein the method comprises flowing reactant materials through at least one catalyst bed in a direction substantially parallel to the
feed axis, and flowing coolant through the plurality of cooling conduits in a direction substantially parallel to the second transverse axis.

[0086] Aspect 25: The method of any one of aspects 22-24, wherein the reactant materials are provided via two or more reactant inlets.


[0088] Although several embodiments of the invention have been disclosed in the foregoing specification, it is understood by those skilled in the art that many modifications and other embodiments of the invention will come to mind to which the invention pertains, having the benefit of the teaching presented in the foregoing description and associated drawings. It is thus understood that the invention is not limited to the specific embodiments disclosed hereinabove, and that many modifications and other embodiments are intended to be included within the scope of the appended claims. Moreover, although specific terms are employed herein, as well as in the claims which follow, they are used only in a generic and descriptive sense, and not for the purposes of limiting the described invention, nor the claims which follow.
What is claimed is:

1. A reactor for producing reaction products, the reactor having a feed axis, a first transverse axis perpendicular to the feed axis, and a second transverse axis perpendicular to the feed axis and the first transverse axis, the reactor comprising:
   - a housing having an outer wall surrounding the feed axis of the reactor;
   - at least one catalyst bed positioned within the housing, wherein the least one catalyst bed catalyst bed is configured to receive one or more catalyst materials; and
   - a plurality of coolant conduits positioned within the housing, wherein each of the at least one catalyst bed and the plurality of coolant conduits are spaced apart relative to the first transverse axis, each coolant conduit having a longitudinal axis oriented substantially parallel to the second transverse axis of the reactor and being configured to receive one or more coolant materials, and permit flow of the one or more coolant materials relative to the second transverse axis,

   wherein the plurality of coolant conduits are positioned in thermal communication with the at least one catalyst bed, and wherein each catalyst bed of the at least one catalyst bed is configured to receive one or more reactant materials flowing relative to the feed axis.

2. The reactor of claim 1, wherein the reactor further comprises one or more reactant inlets, wherein each of the one or more reactant inlets allows flow of a reactant material relative to the feed axis of the reactor; and
   - one or more product outlets, wherein the at least one catalyst bed is positioned between the one or more reactant inlets and the one or more reactant outlets relative to the feed axis.

3. The reactor of claims 1 or 2, wherein the reactor further comprises one or more temperature sensors positioned within the housing.

4. The reactor of claim 3, wherein the reactor further comprises one or more thermowells, wherein the one or more thermowells at least partially surrounds the one or more temperature sensors.
5. The reactor of claims 3 or 4, wherein the one or more temperature sensors are located within the housing in a space between the outer wall of the housing and the least one catalyst bed.

6. The reactor of any one of claims 1-5, wherein each of the at least one catalyst bed has a longitudinal axis oriented substantially parallel to the feed axis of the reactor.

7. The reactor of any one of claims 1-6, wherein the one or more catalyst beds are positioned on one or more catalyst bed supports.

8. The reactor of any one of claims 1-7, wherein the plurality of coolant conduits comprises a plurality of plates arranged to define the plurality of coolant conduits, wherein the plurality of plates arranged have a longitudinal axis substantially parallel to the second transverse axis.

9. The reactor of claim 8, wherein the plurality of plates are adjustable in a direction substantially parallel to the first transverse axis.

10. The reactor of any one of claims 1-9, wherein each of the plurality of coolant conduits has a width of from about 1 mm to about 100 mm.

11. The reactor of any one of claims 2-10, wherein the each of the one or more reactant inlets is in communication with a reactant distributor for distributing reactant material uniformly over the one or more catalyst beds.

12. The reactor of any one of claims 2-11, wherein the reactor comprises two or more reactant inlets.

13. The reactor of any one of claims 1-12, wherein the plurality of the coolant conduits are not tubular in shape.

14. The reactor of any one of claims 1-13, wherein the reactor further comprises a means for adjusting the temperature of the catalyst bed.

15. The reactor of any one of claims 1-14, wherein the plurality of coolant conduits are positioned within the housing to define a space between the plurality of coolant conduits and the outer wall of the housing in a direction parallel to the second transverse axis.

16. The reactor of any one of claims 1-15, the reactor further comprises one or more coolant inlets that are in communication with the plurality of coolant conduits and is
configured to transport coolant through the reactor in a direction relative to the second transverse axis.

17. The reactor of any one of claims 1-15, wherein the reactor is an industrial sized reactor.

18. A reactor system comprising two or more of the reactors of any one of claims 1-17.

19. A method comprising the step of:
   
   a) performing a chemical reaction in a reactor of any one of claims 1-17.

20. A method comprising the step of:
   
   a) performing a chemical reaction in a reactor system of claim 18.
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. B01J8/Q2 B01J8/04 F28D9/O0

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

F28D B01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal , WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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See patent family annex.

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**Date of the actual completion of the international search**

26 January 2017

**Date of mailing of the international search report**

03/03/2017

**Name and mailing address of the ISA/**

European Patent Office, P.B. 5818 Patentlaan 2 NL - 2380 HV Rijswijk  
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