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Method and reactor for conversion of hydrocarbons

Abstract

A reactor and method for the conversion of hydrocarbon gases utilizes a reactor (**12, 312, 412, 512, 612**) having a unique feed assembly with an original vortex combustion chamber (**40, 340, 436, 536, 636**), a diverging conduit (**48, 348, 448, 548, 648**), and a cylindrical reactor chamber (**40, 340, 436, 536, 636**). This design creates a compact reaction zone and an inwardly swirling fluid flow pattern of the feed gases to form a swirling gas mixture that passes through a diverging conduit (**48, 348, 448, 548, 648**). The feed streams can be introduced into the reactor (**12, 312, 412, 512, 612**) at any angle (radial, axial, or something between, or a combination of the above forms) with swirling flow components. The feed streams comprise preheated steam and hydrocarbons for cracking. This system provides conditions suitable for efficient cracking of hydrocarbons, such as ethane, to form olefins.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a National Stage Application under 35 U.S.C. § 371 and claims the benefit of International Application No. PCT/US2021/040414, filed Jul. 6, 2021, which claims the benefit of priority of U.S. Application No. 63/048,210, filed Jul. 6, 2020, the entirety of both of which are incorporated herein by reference.

TECHNICAL FIELD
(1) The disclosure relates to conversion methods for converting a variety of hydrocarbons to produce more valuable products and the reactor designs for such conversion.
BACKGROUND
(2) Conventional steam crackers are the industry go-to reactors to break long-chain hydrocarbons and modify smaller alkanes (i.e., naphtha, butane, or ethane) into smaller molecules and olefins,

such as ethylene and propylene. Examples of such crackers are described in Canadian Patent No. 2555299C and U.S. Pat. Nos. 3,437,714; 4,097,544; and 9,327,260. In such crackers, heavy gases such as naphtha, liquefied petroleum gas (LPG), propane, butane, and ethane are fed into a furnace with steam and converted into smaller olefins. Steam is added to the process to increase the selectivity to olefins with reasonable conversion. Typically, this process operates at high temperatures (i.e., from 750° C. to 900° C.) and have residence times of around 100 to 500 milliseconds. This process has been optimized over the last five decades but there are still significant disadvantages. These include heat losses and complexity associated with separate exothermic (combustion in the furnace) and endothermic steps (cracking in the process tubes). The presence of inert compounds in the combustion and process side also affects the overall efficiency. Metallurgical limitations of the reactors also limit the temperatures that can be used. Ideally, higher temperatures with shorter contact times result in better selectivity and conversion to smaller olefins. Plugging from coking also occurs in these conventional processes, which can increase the capital cost and operational expenses. There is also a lack of feedstock flexibility, as commercial crackers are typically optimized for only a certain type of feedstock.

(3) One solution to these challenges is an ANJEVOC reactor system. The basic ANJEVOC (ANnular JEt VOrtex Chamber) system is disclosed in U.S. Pat. No. 11,020,719, which is incorporated by reference herein for all purposes. U.S. Pat. No. 11,020,719 describes a reactor system that can be used in the pyrolysis conversion of hydrocarbon gases. The ANJEVOC reactor may also be used for cracking, with a somewhat different configuration, referred to as "ANJEVOC-C" the extra "C" for cracking. This cracking system is described in International Publication No. WO2020/086681A2, which is incorporated by reference herein for all purposes.

(4) The disclosure addresses significant changes and improvements in the ANJEVOC-C system.

SUMMARY

(5) The present disclosure primarily uses thermal energy from preheated heated gas to generate the necessary reactions in the reactor. The inlet flows of heated gas and hydrocarbons to be cracked may be partially or completely axial to the central longitudinal axis of the reactor, partially or completely perpendicular to the axis, or some combination thereof, with at least one stream having a certain axial-to-radial velocity ratio, thereby forming a swirling flow in the mixing feed streams. Such a design has many advantages, including intensive turbulent mixing and short mixing time scale leading to high ethylene selectivity, and the heated gas can be condensed out of the outlet stream, which significantly simplifies the downstream separations. If the energy input to the preheating of the heated gas is primarily derived from renewable sources, the CO_2 footprint of this reactor could be extremely small.

(6) In a preferred embodiment, a reactor system for the conversion of hydrocarbons is taught, the system comprising a reactor vessel having a reactor wall that defines a reaction chamber, the reaction chamber having a central longitudinal axis, the reactor vessel having upstream and downstream ends, a diverging conduit having upstream and downstream ends, the circumferential wall expanding in width from the upstream to the downstream ends of the diverging conduit, the downstream end of the diverging conduit being in fluid communication with the reaction chamber of the reactor, a feed assembly having upstream and downstream ends, the downstream end of the feed assembly being operably coupled to the upstream end of the diverging conduit, with the central longitudinal axis passing through the feed assembly, the feed assembly comprising at least two flow inlets, wherein the two flow inlets provide a flow path for at least one each for heated gas and hydrocarbons, respectively. Further, the heated gas and hydrocarbon enter through their respective flow inlets, and mix together as they flow from the feed assembly through the diverging conduit and into the reaction chamber in a swirling mixture. The heated gas is preheated before entering the flow inlet. The heat required for cracking the hydrocarbon in the reaction chamber primarily comes from the preheated heated gas. And finally, the reaction in the reaction chamber creates an exit stream comprising heated gas, hydrocarbon, and reaction products.

(7) In another embodiment, all the flow inlets cause their respective feed streams to enter the reactor in a direction that is approximately perpendicular to the central axis, with at least one stream having a certain tangential-to-radial velocity ratio creating a swirling flow in the mixing feed streams.

(8) In another embodiment, all the flow inlets cause their respective feed streams to enter the reactor in a direction that is approximately axial to the central axis, with at least one stream having a certain tangential-to-axial velocity ratio forming a swirling flow in the mixing feed streams.

(9) In another embodiment, at least one flow inlet causes its respective feed stream to enter the reactor in a direction that is approximately axial to the central longitudinal axis, and at least one inlet flow space causes its respective feed stream to enter the reactor in a direction that is approximately perpendicular to the central longitudinal axis, with at least one feed stream having a tangential-to-axial or tangential-to-radial velocity component to form a swirling flow for mixing in the mixing feed streams.

(10) In another embodiment, the feed assembly further comprises guide vanes, the guide vanes being movable to selected positions to provide selected tangential-to-axial or tangential-to-radial velocity ratios of feed streams for mixing in the mixing feed streams.

(11) In another embodiment, the reaction chamber further comprises an outlet, through which the heated gas, hydrocarbons and reaction products exit the reaction chamber.

(12) In another embodiment, after the heated gas, hydrocarbon and reaction products exit the reaction chamber, the heated gas is separated from the rest of the exit stream.

(13) In another embodiment, the separated heated gas is recycled back to the front of the reactor system.

(14) In another embodiment, the heated gas is preheated via renewable energy sources.

(15) In another embodiment, at least one of the feed inlets is an atomizer, the atomizer providing a flow path for the hydrocarbon.

(16) In another embodiment, the feed stream coming in via the atomizer is naphtha, crude oil, pyoil (from hydrocarbons, biomass, or plastic waste), or NGL in liquid phase.

(17) In another embodiment, the reaction chamber has an outer wall, and wherein the selection and placement of the one or more flow inlets allows one to control the placement of the hydrocarbon with respect to the heated gas, the placement creating a relatively cooler space in the interior of the reactor.

(18) In another embodiment, the hydrocarbon first enters the reactor closest to the outer wall of the reactor, and then moves radially inward to interact with the heated gas.

(19) In another embodiment, the hydrocarbon first enters the reactor closest to the central longitudinal axis of the reactor, and then moves radially outward to interact with the heated gas.

(20) In another embodiment, the reactor system further comprises a converging conduit, the converging conduit having an upstream and downstream end, the central longitudinal axis passing through the converging conduit, the converging conduit being connected to the upstream end of the diverging conduit, and the upstream end of the feed assembly.

(21) In another embodiment, the converging conduit and the diverging conduit together comprise a venturi.

(22) In another embodiment, the swirl atomizer may or may not help induce swirling in the mixing feed streams.

(23) In another embodiment, the heated gas is steam. And in another embodiment, any of the feed steams contain impurities.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) For a more complete understanding of the embodiments described herein, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying figures, in which:

(2) FIG. **1** is a process flow diagram of a cracking system for cracking of hydrocarbons into cracked hydrocarbon products in accordance with particular embodiments of the disclosure;

(3) FIG. **2** is a schematic representation of an embodiment of the reactor system for cracking shown in cross section;

(4) FIG. **3** is a partial schematic representation of an improved lower or upstream portion of the reactor system showing a reactor feed assembly and portion of the reactor, constructed in accordance with particular embodiments of the disclosure;

(5) FIG. **4** is partial schematic representation of a lower or upstream portion of the reactor system showing a reactor feed assembly and portion of the reactor, constructed in accordance with particular embodiments of the disclosure;

(6) FIG. **5** is partial schematic representation of a lower or upstream portion of the reactor system showing a reactor feed assembly and portion of the reactor, constructed in accordance with particular embodiments of the disclosure;

(7) FIG. **6** is partial schematic representation of a lower or upstream portion of the reactor system showing a reactor feed assembly and portion of the reactor, constructed in accordance with particular embodiments of the disclosure;

(8) FIG. **7** shows the mass of the process of Example 1; and

(9) FIG. **8** shows the product gas species mole fraction distribution in Example 1 presented on a dry basis.

DETAILED DESCRIPTION

(10) In the present disclosure, a novel system is utilized that converts hydrocarbons to higher value products, such as olefins, by utilizing high centrifugal forces in a unique reactor configuration to create and control a reacting flow environment that maximizes the production of desirable olefins with very high productivity (cracking). This is achieved by utilizing annular highly swirled jets of feed gases where hydrocarbons and preheated steam are mixed to crack the hydrocarbons. In one embodiment, the cracking reactor used can be similar to the pyrolysis reactor described in International Publication No. WO2020/086681A2, which is incorporated by reference herein for all purposes. International Publication No. WO2020/086681A2 describes a reactor that can be used in the pyrolysis cracking of hydrocarbon gases. This type of reactor may be referred to as an ANJEVOC-C (ANnular JEt VOrtex Chamber-Cracking) reactor.

(11) Referring to FIG. **1**, a flow schematic of a hydrocarbon conversion system **10** is shown for the conversion of hydrocarbons to higher value products, such as olefins. The system **10** includes an ANJEVOC-C cracking reactor **12**, which is described in more detail later on. A cracking feed **14** is fed to the reactor **12** as a separate stream. The cracking feed **14** can include hydrocarbons such as ethane, liquefied petroleum gas (LPG), butane, natural gas liquid (NGL), natural gas, light gas oils, and/or heavy gas oils, or a blend of these hydrocarbons. The cracking feed stream **14** may be preheated prior to being introduced into the reactor **12**. In particular applications, the feed stream **14** may be heated to a temperature of from 25° C. to 500° C. to improve conversion efficiency or vaporize heavier liquid hydrocarbons either externally or within the reactor.

(12) It should be noted in the description, if a numerical value, concentration or range is presented, each numerical value should be read once as modified by the term "about" (unless already expressly so modified), and then read again as not so modified unless otherwise indicated in context. Also, in the description, it should be understood that an amount range listed or described as being useful, suitable, or the like, is intended that any and every value within the range, including the end points, is to be considered as having been stated. For example, "a range of from 1 to 10" is

to be read as indicating each and every possible number along the continuum between about 1 and about 10. Thus, even if specific points within the range, or even no point within the range, are explicitly identified or referred to, it is to be understood that the inventor appreciates and understands that any and all points within the range are to be considered to have been specified, and that inventor possesses the entire range and all points within the range.

(13) A feed stream containing a heated gas is also fed to the reactor **12** as a separate stream **18**. In some embodiments, the heated gas is steam, and in such instances the feed stream would be a steam feed stream **18**. For purposes of discussion, steam will be used as an illustrative example of a possible heated gas, but any other heated gas would also work just as well, and the use of steam in this discussion is not meant in any way to be a limitation of the disclosure.

(14) The steam feed stream **18** is preheated to a sufficient temperature to allow cracking of the cracking feed stream **14**, once the two are mixed in the reactor **12**. The steam feed stream **18** will include both recycled steam **30** coming back from the exit of the separator, as well as make-up steam **16** coming from another source. The volume ratio of steam and cracking feed **14** is preferably optimized to achieve at least 1500 K after fully mixing, ensuring enough thermal energy for the endothermic cracking reactions.

(15) Cracked reaction products **20** are removed from the reactor **12** where they may be cooled by quenching in a quenching unit **22**, such as a water-droplet-spray quench vessel, or other suitable gas quench devices. The cracked products **20** will typically be a mixture of ethane, ethylene, acetylene, methane, hydrogen gas, steam, water, oxygenates, some heavies (>C4), some aromatics, and product olefins.

(16) The quenched cracked reaction products **24** may be delivered to a separation unit **26**, where the condensed water and steam are separated out for recycling in a recycle stream **30**. Another recycle stream of unreacted products **35** is also removed and sent back to a point ahead of the reactor to mix with the hydrocarbon feed **14**. Finally, the remaining portions of the product stream **28** containing product olefins, such as ethylene (C_2H_4), acetylene (C_2H_2), propylene (C_3H_6), and others, continue onward for further processing.

(17) The separated water and steam stream **30** is removed from the separator **26** and passed through another heat exchanger **32** to convert any water to steam and then heat the steam up to cracking temperatures. One or more heat exchangers **32** may be used to achieve the desired temperatures. The recycled steam stream **32** then mixes with any additional needed new steam via make-up steam stream **16**, the make-up steam stream heated by another heat exchanger **34**, to create an appropriate ratio of steam to hydrocarbon, prior to entry into the reactor. The heat exchanger(s) may instead be utilized after the two steam streams have mixed, or some combination thereof.

(18) The ratio of hydrocarbons to steam depends on the preheating temperature of these two streams. The goal is to reach a temperature in the range of 1500 K to 2000 K after fully mixing to ensure acceptable once-through conversion. If the temperature is too low, the conversion will be low, while if the temperature is too high, selectivity of C_2H_2 will be reduced. The steam feed stream is mainly used as a thermal carrier to crack hydrocarbon feed, while the reaction between steam and hydrocarbon is minimum. Therefore, the make-up stream is a small portion of the recycled steam stream.

(19) It should be noted that while the system **10** of FIG. **1** shows single units for the various process steps, each unit could be composed of one or more units that may operate in conjunction with one another, such as in parallel or sequentially, to carry out the various process steps described.

(20) Referring to FIG. **2**, an elevational cross-sectional schematic representation of the cracking reactor system **12** for cracking of hydrocarbons, such as ethane, LPG, butane, naphtha, natural gas, light gas oils, heavy gas oils, or a combination of these hydrocarbons, is shown. The reactor **12** constitutes an ANJEVOC-C reactor and includes a reactor vessel **36** having a reactor wall **38** that defines an interior reaction chamber **40**. The reactor wall **38** may have a cylindrical configuration

with a constant diameter along all or a portion of its length, which may constitute a majority of its length. In most instances, the reactor **12** is oriented vertically so that the cylindrical reactor wall **38** is oriented in an upright orientation. The reactor can have other orientations (e.g., horizontal, sloped), however, because the process is controlled by the centrifugal force, which exceeds the gravitational force by several orders of magnitude. The reactor vessel **36** may be configured to provide a length to diameter ratio (L/D) of at least 2. In particular applications, the L/D ratio may range from 2-10.

(21) The reactor vessel **36** may be formed from steel. In certain embodiments, a cooling jacket can be provided around the reactor vessel, wherein a second steel wall **42** is positioned around and spaced from the inner reactor wall **38** and a cooling fluid, such as water may be circulated through the jacket formed between the walls **38**, **42**. In other embodiments, the reactor wall **38** may be formed from one or more layers of refractory material that line the interior of an outer steel wall to reduce heat loss and sustain the high temperatures of the reactor **12**. As will be described later on, because of the unique design and operation of the reactor **12**, the reactor wall **38** is cooled internally by the high-velocity near-wall gas flow pushed by centrifugal forces against the reactor wall **38** so that in some applications no exterior cooling jacket is required. This also allows refractory materials to be used for the interior of the reactor wall **38**. Further, as no oxygen or oxygen-based fuel is used, the peak temperatures will not exceed 2000 K.

(22) An outlet **44** is provided at the upper or downstream end of the reactor vessel **36** for removing or discharging cracked products from the reaction chamber **40**. Although the outlet **44** is shown located at the upper end of the reactor vessel **36**, in other embodiments it may be located at the lower end of the reactor vessel **36**, so that the flow through the reactor is in the opposite direction (i.e., from top to bottom). The outlet diameter can be same as the diameter of the reactor wall **38** or the outlet diameter may be reduced to accelerate the flow before quenching and collection downstream.

(23) The reactor **12** includes a reactor inlet assembly **46** that is coupled or joined to the lower or upstream end of the reactor wall **38** of the reactor vessel **36**. The inlet assembly **46** has a diverging conduit **48** with a circumferential wall **50** that surrounds a central longitudinal axis **52** of the reactor. Where the reactor **12** is oriented vertically, the central axis **52** will also be oriented vertically as well and will be concentric with or parallel to a central vertical axis of the reactor vessel **36**. In the embodiment shown, the axis **52** is concentric with and aligned with the central longitudinal axis of the reactor vessel **36**. The circumferential wall **50** extends from opposite upstream and downstream ends of the diverging conduit **48**. As used herein, the terms "upstream" and "downstream" or similar expressions with respect to describing various components of the reactor system **12** shall refer to the position of the component with respect to the direction of overall fluid flow through the reactor **12** along the central axis **52**. A converging conduit **54** having an upstream and downstream end, with the central longitudinal axis **52** passing through the converging conduit **54**, is connected to the upstream end of the diverging conduit **48**, and the upstream end of the feed or reactor inlet assembly **46** to form a venturi. As can be seen in FIG. **2**, the circumferential wall **50** smoothly expands in width or diameter from the upstream end to the downstream end of the diverging conduit **48**. The interior of the circumferential wall **50** may have a circular perpendicular transverse cross section (with respect to the axis **52**) along its length. The circumferential wall **50** defines an interior flow path of the inlet assembly **46**.

(24) The diverging conduit **48**, as well as the other diverging conduits described herein, is configured for non-supersonic fluid flow. Conduits or nozzles configured for supersonic flow, such as de Laval nozzles, are configured differently from the conduit **48** to provide supersonic flow downstream to form a shockwave. The diverging conduit **48** does not form such supersonic flow or shockwave. Instead, the conduit **48** has a geometry that facilitates a recirculation and backflow of gases within the interior reaction chamber **40** near the central longitudinal axis **52** in combination with annular swirling jet gas flow adjacent to the inner reactor wall **38**. As such, the diverging

conduit **48** will have a greater angle of divergence than the angle of divergence typically utilized in de Laval nozzles (e.g., 15° or less). In, certain embodiments, the overall angle of divergence "A" (FIG. **2**) relative to the axis **52** may be from 25° or more. In particular instances, the angle of divergence A for the diverging conduits discussed herein is from 25° to 55°. In some embodiments, the angle of divergence A is of from at least, equal to, and/or between any two of 25°, 26°, 27°, 28°, 29°, 30°, 31°, 32°, 33°, 34°, 35°, 36°, 37°, 38°, 39°, 40°, 41°, 42°, 43°, 44°, 45°, 46°, 47°, 48°, 49°, 50°, 51°, 52°, 53°, 54°, and 55°. The large divergence angle does not lead to recirculation of the flow at the walls as in this unique design the upstream swirling flow is coupled with the convergent divergent nozzle.

(25) The downstream end of the diverging conduit **48** or converging conduit **54** joins the reactor wall **38** around its perimeter so that the diverging conduit **48** is in fluid communication with the reactor chamber **40** of the cracking reactor vessel **36**. The upstream end of the diverging conduit **48** forms a reactor inlet **56** of the reactor vessel **36**.

(26) A reactor feed assembly **58** is provided with the reactor **12**. The reactor feed assembly **58** is in fluid communication with the reactor inlet **56** of the inlet assembly **46**, with the central axis **52** passing through the reactor feed assembly **58**. The feed assembly **58** includes a downstream feed assembly wall **60** that extends circumferentially around and joins the upstream end of the reactor inlet **56**. The feed assembly wall **60** is oriented perpendicular or substantially perpendicular (i.e., ≤5 degrees from perpendicular about its circumference) to the central axis **52**.

(27) Axially spaced upstream from the downstream wall **60** along the central axis **52** is an upstream feed assembly wall **62**. The upstream wall **62** is perpendicular to or substantially perpendicular (i.e., ≤5 degrees from perpendicular about its circumference as it extends from the central axis) to the central axis **52** and extends across the central axis **52**.

(28) A gas partition wall **66** is axially spaced between the downstream and upstream feed assembly walls **60**, **62**. The partition wall **66** is also oriented perpendicular to or substantially perpendicular (i.e., ≤5 degrees from perpendicular about its circumference as it extends from the central axis) to the central axis **52**, having a central opening **70** that surrounds the central axis **52** and is concentric with the diverging conduit **48**. The central opening **70** has a circular configuration. Other shapes for the central opening **70** (e.g., oval) may also be used provided such configuration facilitates the swirling of gases to provide the required flow patterns described herein. This shape may also correspond to the cross-sectional shape of the circumferential wall **50** of the diverging conduit **48**. In most applications, however, the central opening **70** will be circular in shape. The central opening **70** may have a diameter or width that is the same or slightly different (i.e., greater or smaller) than the diameter or width of the diverging conduit **48** at its narrowest point.

(29) An annular gas flow space **74** is defined by the downstream side of the downstream partition wall **66** and the downstream feed assembly wall **60**. The flow space **74** may constitute an annular steam inlet flow space, or it may be used as a hydrocarbon annular flow space.

(30) A further annular flow space **76** is defined between the upstream side of the downstream gas partition wall **66** and the downstream side of the upstream feed assembly wall **62**. The flow space **76** constitutes an annular inlet flow space that again may be used for either steam or hydrocarbons.

(31) This configuration provides flow passages through which hydrocarbon gas feed to be cracked and steam for providing cracking heat can each be separately introduced and passed through the flow spaces **74**, **76**, respectively, to the central axis **52** of the diverging conduit **48**. In most cases, the lowermost or upstream flow space **76** will constitute a hydrocarbon cracking feed inlet flow space. The steam feed is more preferably introduced into the uppermost or downstream annular steam inlet flow space **74**.

(32) The flow passages **74**, **76** are configured so that the different feeds pass through flow spaces to the central axis **52** of the diverging conduit **48** in an inwardly swirling fluid flow pattern within said flow spaces so that the feeds flow about the central axis **52** of the diverging conduit **48**.

(33) The walls **60**, **62**, **66** forming the flow spaces **74**, **76** are sized and axially spaced apart to

provide the desired volume and flow characteristics for the gases flowing through them. This may be based upon the desired flow rates or linear velocities of each of the feed gases and their relative amounts.

(34) Annular gas manifolds **90**, **88** may be provided around the outer periphery of the flow spaces **74**, **76**, respectively. The gas manifold **88** may be fluidly coupled to a cracking feed source, such as cracking feed **14** of FIG. **1**. The manifold **90** may be fluidly coupled to a steam source, such as the steam feed **18** of FIG. **1**.

(35) Gas inlets **98**, **102** from the manifolds **90**, **88**, respectively, may be directed tangentially into the flow spaces **74**, **76** so that the gases are not directed only radially toward the central axis **52** from the inlets **98**, **102**, but instead are directed mostly tangentially around the central axis **52** to provide an inwardly swirling flow pattern. Furthermore, the walls **60**, **62**, **66** forming the different flow spaces of the feed assembly **58** keep the gases introduced from the manifolds **88**, **90** from flowing axially along the central axis **52** while they are contained within the flow spaces **74**, **76**. The manifolds **88**, **90** can be configured as standard manifolds (e.g., snail-like) as may be typically used in vortex devices.

(36) Referring again to FIG. **2**, the area extending from the central opening **70** of the partition wall **66** to the reactor inlet **56** define a mixing chamber **116**. It is here that hydrocarbon cracking feed from the upstream hydrocarbon feed inlet flow space **76** and steam from flow space **74** are discharged into the mixing chamber **116** so that hydrocarbon cracking feed and steam are mixed together and form a swirling gas mixture within the mixing chamber **116**. This swirling gas mixture then passes through the diverging conduit **48** and into the reaction chamber **40** of the reactor vessel **36**.

(37) Diverters **106**, **108** may also be used to provide for changing the angle of attack of the stream flows coming into the mixing chamber **116**, typically to add some element of tangential flow.

(38) The gases are introduced and flow through the flow spaces **74**, **76** so that the axial velocity (i.e., relative to the axis **52**) is controlled in being discharged into the mixing chamber **116**. The inlets **98**, **100** and/or the orientation of the guide vanes **106**, **108** may be set for each flow space **74**, **76** so that a selected azimuthal-to-radial velocity for each of the feed streams that flow through the flow spaces **74**, **76** is achieved. With respect to the azimuthal-to-radial velocity, in particular embodiments, this may range from 0 to 30 or more, more particularly from 0, 1, or 2 to 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, or 30. In some applications the azimuthal-to-radial velocity may range from 0 to 20, more particularly from 3 to 10. The particular azimuthal-to-radial ratio may vary depending upon the particular reactor configuration and composition of the various streams, however. This is more intimately related to the mixing times and reaction times depending on the flow rates, as well as the composition of the feedstocks used for cracking.

(39) The preheated steam, when mixed with the hydrocarbon feed starting in mixing chamber **116** and flowing up through the reactor chamber **40**, provides the heat needed to crack the hydrocarbon. Cracked hydrocarbon products produced in the reactor along with the preheated steam are removed from the reactor vessel **36** through outlet **44**, where they may be quenched and further processed and recycled, as discussed with respect to the process steps previously described for FIG. **1**.

(40) Referring now to FIG. **3**, an elevational cross-sectional schematic representation of a lower portion of one embodiment of the inventive cracking reactor system **312** for cracking of hydrocarbons, such as ethane, LPG, butane, naphtha, natural gas, light gas oils, heavy gas oils, or a combination of these hydrocarbons, is shown. The reactor **312** constitutes an ANJEVOC-C reactor and includes a reactor vessel **336** having a reactor wall **338** that defines an interior reaction chamber **340**. The reactor wall **338** may have a cylindrical configuration with a constant diameter along all or a portion of its length, which may constitute a majority of its length. In most instances, the reactor **312** is oriented vertically so that the cylindrical reactor wall **338** is oriented in an upright orientation. The reactor can have other orientations (e.g., horizontal, sloped), however, because the

process is controlled by the centrifugal force, which exceeds the gravitational force by several orders of magnitude. The reactor vessel **336** may be configured to provide a length to diameter ratio (L/D) of at least 2. In particular applications, the L/D ratio may range from 2-10.

(41) The reactor vessel **336** may be formed from steel. In certain embodiments, a cooling jacket (not shown) can be provided around the reactor vessel as taught in the prior art. In other embodiments, the reactor wall **338** may be formed from one or more layers of refractory material that line the interior of an outer steel wall to reduce heat loss and sustain the high temperatures of the reactor **312**. Or as described elsewhere in this application, because of the unique design and operation of the reactor **312**, the reactor wall **338** may be cooled internally by the high-velocity near-wall gas flow pushed by centrifugal forces against the reactor wall **338** so that in some applications no exterior cooling jacket is required. This also allows refractory materials to be used for the interior of the reactor wall **338**. Refractory materials (without cooling) typically cannot be used with conventional cracking reactors with pure oxygen due to the higher temperatures (˜2800° C.) encountered.

(42) Where the reactor **312** is oriented vertically, a central axis **352** will also be oriented vertically as well and will be concentric with or parallel to a central vertical axis of the reactor vessel **336**. In the embodiment shown, the central axis **352** is concentric with and aligned with the central longitudinal axis of the reactor vessel **336**.

(43) An outlet (not shown) is provided at the upper or downstream end of the reactor vessel **336** for removing or discharging cracked products from the reaction chamber **340**. As used herein, the terms "upstream" and "downstream" or similar expressions with respect to describing various components of the reactor system **312** shall refer to the position of the component with respect to the direction of overall fluid flow through the reactor **312** along the central axis **352**. The outlet may be located at the upper end of the reactor vessel **336**, or in other embodiments it may be located at the lower end of the reactor vessel **336**, so that the flow through the reactor is in the opposite direction (i.e., from top to bottom). The outlet diameter can be the same as the diameter of the reactor wall **338** or the outlet diameter may be reduced to accelerate the flow before quenching and collection downstream.

(44) The reactor **312** further includes a diverging conduit **348**. The diverging conduit **348** has a circumferential wall **350** that surrounds the central longitudinal axis **352** of the reactor, the circumferential wall **350** being coupled or joined to the lower or upstream end of the reactor wall **338** of the reactor vessel **336**. The circumferential wall **350** extends from opposite upstream and downstream ends of the diverging conduit **348**.

(45) As can be seen in FIG. **3**, the circumferential wall **350** smoothly expands in width or diameter from the upstream end to the downstream end. The interior of the circumferential wall **350** may have a circular perpendicular transverse cross section (with respect to the axis **352**) along its length. The circumferential wall **350** defines an interior flow path of the reactor feed assembly **358**. While the diverging conduit **348** is shown in FIG. **3** as a linearly expanding form, it may take other shapes and rates of change of diameter. The overall angle of divergence of the conduit **348** or wall **350** may be the same as that described for reactor **12** of FIG. **2**. The downstream end of the diverging conduit **348** joins the reactor wall **338** around its perimeter so that the diverging conduit **348** is in fluid communication with the reactor chamber **340** of the cracking reactor vessel **336**. The upstream end of the diverging conduit **348** is connected to the reactor feed assembly **358** of the reactor vessel **336**.

(46) The feed assembly **358** includes an outer feed assembly wall **360** that extends circumferentially around and joins the upstream end of the diverging conduit inlet **356**. The feed assembly wall **360** is oriented parallel or substantially parallel (i.e., ≤5 degrees from axial about its circumference) to the central axis **352**. While only a portion of the reactor **312** is shown, the feed assembly extends concentrically about the entire circumference of the upstream end of the diverging conduit **348**.

(47) A gas partition wall **364** is provided between the downstream and upstream ends of the feed assembly. The partition wall **364** is also oriented parallel or substantially parallel (i.e., ≤5 degrees from axial with regard to the central axis) to the central axis **352**.

(48) An inner wall **366** is positioned parallel to the partition wall **364**, and closer to the central axis **352**. The inner wall **366** is also oriented parallel or substantially parallel (i.e., ≤5 degrees from axial about its circumference) to the central axis **352**. It is connected to a mixing chamber upstream wall **380**. Upstream wall **380** is shown oriented perpendicular or substantially perpendicular (i.e., ≤5 degrees from perpendicular about its circumference) to the central axis **352**, though in fact it may be a various other angles that may be of benefit to generating the desired swirling of the gases.

(49) Walls **360**, **364** define a first annular gas flow space **372**. Likewise, walls **364**, **366** define a second annular gas flow space **374**. These annular gas flow spaces are utilized to input the two feeds into the reactor, preheated steam and hydrocarbons. Which feed stream goes through which annular gas flow space depends on the preferred conditions inside the reactor **336**, such as where to have hotter and colder portions of the gas mix inside the reactor, with respect to the outer wall **338**. For instance, hydrocarbons for cracking could enter the reactor via flow space **374** while the super-heated steam enters through flow space **372**. Such a configuration, with appropriate flow rates, would create a higher heat region inside the reactor **336**, with hot reaction gases closer to the reactor wall **338** and relatively colder feedstock closer to the central axis **352**. In another preferred embodiment, the two feeds could be reversed. This would cause the hot reaction gases to be in the core of the reactor **336**, around the central axis **352**, while the colder feedstock gases would be next to the reactor wall **338**. Thereby, less heat resistant materials would be needed for the reactor wall **338**, lowering the expense of building the reactor **336**.

(50) While shown here with two inlets, there can be in fact any number of flow inlets, based on the number of partition walls. Further, these annular gas flow spaces **372**, **374** are approximately aligned with the diverging conduit **348** and circumscribe the central axis **352**. The annular gas flow spaces **372**, **374** each preferably have an annular configuration. Other shapes for the spaces **372**, **374** may also be used provided such configuration facilitates the swirling of gases to provide the required flow patterns described herein. This shape may also correspond to the cross-sectional shape of the circumferential wall **350** of the diverging conduit **348**. In most applications, however, the flow spaces **372**, **374** will be annular in shape. The flow spaces **372**, **374** may have a diameter or width that is the same or slightly different than the diameter or width of the diverging conduit **348** at its narrowest point.

(51) Finally, flow spaces **372**, **374** further comprises guide vanes **304**, **306**. Each guide vane **304**, **306** can help control the direction of how their respective feed goes into the reactor, preferably to assist in creating a swirling effect, as discussed further infra. Importantly, the direction of the flow spaces **372**, **374** along with the guide vanes **304**, **306** assure that the gases are not directed only axially along the central axis **352** from the inlets **372**, **374**, but instead are directed mostly radially and tangentially around the central axis **352** to provide an inwardly swirling flow pattern. The walls **360**, **364**, **366** forming the flow spaces **372**, **374** are arranged to provide the desired volume and flow characteristics for the gases flowing through them. This may be based upon the desired flow rates or linear velocities of each of the feed gases and their relative amounts.

(52) Referring to FIG. **3**, in operation, a cracking hydrocarbon feed is introduced into flow space **372**. The hydrocarbon feed may be ethane, LPG, butane, naphtha, natural gas, light gas oils, heavy gas oils, or their combinations. While these cracking feed materials are typically introduced as gases, in some instances they may be introduced as liquids. Once introduced as liquids they are rapidly vaporized within the reactor. This may be beneficial in that light and heavy gas oils, for example, are typically vaporized outside the reactor in conventional cracking systems. Such exterior vaporization creates coking issues, however. By injecting them directly into the reactor in liquid form, these issues are avoided. The cracking feed will typically be denser than the heated steam. This is a result of both the high molecular weight of the cracking feed and its density at the

selected temperature of the cracking feed. The denser gas/liquids move outward while the lighter cracked products move inward due to very high centrifugal acceleration (100,000-1M g forces). The denser hydrocarbons rapidly mix into the peripheral heated steam at very high temperature due to high swirl.

(53) Preheated steam is introduced into the other gas flow space **374**. The introduced steam provides the heat needed to facilitate the actual cracking within the reactor **312**. For certain applications (like an example discussed later on), steam may be used in a mass ratio of steam-to-hydrocarbon of 4, or greater.

(54) Such an arrangement again alters the mixing and swirling characteristics inside the reactor compared to that of the reactor of FIG. **2**, thereby altering the reaction kinetics and thus the conversion, selectivity and yield coming out of the reactor **312**. Determining improved and potentially optimal flow characteristics can be accomplished via experimental tests, or via modern sophisticated modeling tools as is known in the art. Importantly, this illustrates the concept that improvements can be made in the performance of the reactor by varying the angle of the inlet flows of the various components. Indeed, while the various flows are shown in these examples as being either axial, perpendicular, or some of each, any other angles would be acceptable. Importantly, swirling is desired to create the rapid mixing and cracking of the hydrocarbons.

(55) Referring now to FIG. **4**, another embodiment of the disclosure is disclosed. Similar to the embodiment in FIG. **3**, the reactor **412** comprises a reactor vessel **436** having a reactor wall **438**. A diverging conduit **448** is connected to the reactor wall **438** and may have an angle of divergence that is the same as that previously described. In turn, the diverging conduit **448** is connected to a reactor feed assembly **458**. The feed assembly **458** comprises two flow spaces **474**, **478**. In this embodiment, flow space **478** enters the feed assembly **458** perpendicular to the central axis **452**. The remaining flow space **474** still flows into the feed assembly **458** parallel to the central axis. In such a configuration, the hydrocarbon feedstock would enter the feed assembly **458** from flow space **474**, while the heated steam stream would enter via flow space **478**. In another preferred embodiment, the two feeds could be reversed. Mixing chamber upstream walls **480**, **460**, **476** may have varying lengths to control possible expansion ahead of actual contact of the flow streams **474**, **478**.

(56) Flow spaces **474**, **478** further comprises guide vanes **462**, **464**, respectively. Each guide vane **462**, **464** can assist in controlling the direction of how their respective feed goes into the reactor, preferably to assist in creating a swirling effect, as discussed further infra. Importantly, the direction of the flow spaces **474**, **478** along with the guide vanes **462**, **464** assure that the gases are not directed only axial or perpendicular compared to the central axis **452** from the inlets **474**, **478**, but instead are directed mostly radially and tangentially around the central axis **352** to provide an inwardly swirling flow pattern.

(57) Such an arrangement as shown in FIG. **4** again alters the mixing and swirling characteristics inside the reactor compared to that of the reactor of FIGS. **2** and **3**, thereby altering the reaction kinetics and thus the conversion, selectivity and yield coming out of the reactor **412**. Determining improved and potentially optimal flow characteristics can be accomplished via experimental tests, or via modern sophisticated modeling tools as is known in the art. Importantly, this illustrates the concept that improvements can be made in the performance of the reactor by varying the angle of the inlet flows of the various combustion components. Indeed, while the various flows are shown in these examples as being either axial, perpendicular, or some of each, any other angles would be acceptable. Importantly, swirling is desired to create the rapid mixing and cracking of the hydrocarbons.

(58) Referring now to FIG. **5**, another embodiment of the disclosure is disclosed. Similar to the embodiments in FIGS. **3** and **4**, the reactor **512** comprises a reactor vessel **536** having a reactor wall **538**, the reactor wall **538** coupled to a diverging conduit **548** which in turn is connected to a reactor feed assembly **558**. In this instance, one flow space **574** enters the feed assembly **558** parallel to the

central axis **552**. In addition, an atomizer **590** is positioned closer to the central axis **552**, compared to the flow space **574**, and is also parallel with the central axis **552**. In a preferred embodiment, the atomizer **590** is positioned directly in line with the central axis **552**. The atomizer **590** is used to inject liquid hydrocarbon feedstocks, while flow spaces **574** is used to inject the preheated steam stream. The flow space **574** further includes a guide vane **562**, to allow the flow stream entering via **574** to be angled in various ways, to improve the necessary swirling effects. Mixing chamber upstream walls **580**, **560** may have varying lengths to control possible expansion ahead of actual contact of the flow streams **474** and **478**. In another preferred embodiment, several atomizers **590** can also be angled slightly off from parallel to the central axis **552** with tangential injection velocity to aid in generating swirling in the mixing.

(59) Again, having the hydrocarbon feed stream most inward means that the outer walls of the reactor vessel **536** will be where the hot reaction gases will be during operation, while the core of the reactor vessel **536** will be cooler due to the hydrocarbon feed stream, entering via the atomizer.

(60) Referring now to FIG. **6**, another embodiment of the disclosure is disclosed. Similar to the embodiments in FIGS. **3**, **4** and **5**, the reactor **612** comprises a reactor vessel **636** having a reactor wall **638**, the reactor wall **638** coupled to a diverging conduit **648** which in turn is connected to a reactor feed assembly **658**. In this instance, a flow space **674** enters the feed assembly **658** perpendicular to the central axis **652**. In addition, an atomizer **690** is positioned close to the central axis **652**, compared to the flow space **674**, and is parallel with the central axis **652**. In a preferred embodiment, the atomizer **690** is centered with the central axis **652**. The atomizer **690** is used to inject liquid hydrocarbon feedstocks, while flow space **674** is used to inject the high temperature steam stream. An inner wall **680** is proximate to the atomizer **690**, the inner wall **680** also being perpendicular to the central axis **652** to serve as a bottom wall in the reactor. An inner wall **660** may be place between the entrance of the flow space **674** into the feed assembly **658** and the diverging conduit **648**. This inner wall **660** controls how close to the central axis **652** the high temperature steam enters the feed assembly **658**.

(61) Again, having the hydrocarbon feed stream most inward means that the outer walls of the reactor vessel **636** will be where the hot reaction gases will be during operation, while the core of the reactor vessel **636** will be cooler due to the hydrocarbon feed stream, entering via the atomizer. And importantly, the direction of the flow space **674** and the atomizer **690**, along with the guide vane **662** assure that the gases are not directed only parallel or perpendicular to the central axis **652**, but instead are directed mostly radially and tangentially around the central axis **652** to provide an inwardly swirling flow pattern.

(62) In each case, from FIG. **2** to FIG. **6**, the volumetric flow rates are controlled to create a swirling pattern inside the reactor, thereby creating a superior reaction, with high yields and conversion. Optimal flow rates for all the various flow streams, along with actual compositional details, and shape of the reactor, are all modeled via software to optimize the results of the reaction. Of note, if one wants to keep the walls relatively cool, then one can use a design as shown if FIG. **3** or **4**, and make sure the steam starts more in the middle. If one prefers the coolest part of the reactor chamber to be towards the center, then one can use any of these designs and have the steam start more on the outside portion of the reactor.

(63) The reaction temperature within the reactor and recirculation zone of the present disclosure may range from 900° C. to 1300° C. In particular embodiments, the temperature within the reactor and recirculation zone may range from 1000° C. to 1300° C., more particularly from 1200° C. to 1250° C. In some embodiments, the reactor temperature is higher than what is achieved in conventional cracking reactors, such as tube furnace reactors, which typically operate at 800° C. to 900° C. As discussed earlier, this is due to the temperature limitations of the metallic materials used for such conventional reactors. In the present case, the swirling gas mixture facilitates keeping the walls of the reactor much cooler than in such conventional reactors. The use of such higher temperatures also allow a shorter residence or contact times, thereby resulting in better selectivity

and conversion without formation of unwanted products. Operating temperatures for the reactor may be selected to avoid excess production of such unwanted compounds, such as acetylene.

(64) The reactor design described herein features high conversion of the cracking feed and higher selectivity for olefins than other conventional cracking methods. The reactor is relatively simple in configuration, which can significantly reduce the capital and operating costs. The high-swirling gas mixture provides a stable and compact reaction zone, first in the feed assembly then into the main reactor. The reactor walls may be cooled by the swirling hydrocarbon flow against the wall allowing for higher temperatures in the reactor, requiring shorter residence times, so that more desirable products (e.g., ethylene) are produced. Maintaining lower reactor wall temperatures also allows refractory materials to be used in place of metal materials and thus minimizing heat loss.

(65) Because the heated combustion gases are directly mixed with cracking feed in the swirling gas mixture, there is direct gas-gas heat transfer to carry out the cracking reactions. This differs from conventional cracking reactors, such as tube furnaces, which rely on non-direct heat transfer where heat is transferred through the tube walls of the reactor from a separate heating source, such as external combustion gases. Here the process is intensified in that the exothermic step of providing heat from the preheated steam stream to the hydrocarbon feed is immediately combined with the endothermic step of cracking the cracking feed. Thus, energy losses due to heat transfer through reactor walls and equipment, as with conventional systems, are eliminated or minimized. The reactor can be scaled up by increasing feeding rate and dimension scale up.

(66) The streams do not need to be pure, and it is understood that the streams may contain impurities, as can commonly occur, and they may have a potentially negative effect on the results of the reactor. The described reactor will still work in such conditions, though potentially without as great of efficiency.

(67) In some instances, one may add additional streams to generate extra heat. For instance, one could add streams of oxygen and methane to react and generate additional heat.

(68) The following examples serve to further illustrate various embodiments and applications.

EXAMPLES

Example 1

(69) Computational Fluid Dynamics (CFD) simulations with these configurations have been conducted to support the design concept. In one example, inlet steam and ethane were preheated, so that a final mixture temperature of 1500 K was achieved. The following flow rates and temperatures were used for the simulation and are presented in Table 1 below.

(70) TABLE-US-00001

TABLE 1

	Steam	C2H6
Heat Capacity J/kg° K	2300	4000
Mass Flow Rate kg/s	0.02173913	0.005
Initial Temp. ° K	1800	750
Final Temp. ° K	1500	1500
Heat Exchange W	15,000	−15,000

(71) FIGS. **7** and **8** show the mass balance of the cracking process, and product gas species mole fraction in dry basis (steam free). In this simulation, ethane conversion was 53.2%. Ethylene and acetylene selectivity was 92.3%, and the yield of ethylene and acetylene was 49.2%.

(72) While the disclosure has been shown in some of its forms, it should be apparent to those skilled in the art that it is not so limited, but is susceptible to various changes and modifications without departing from the scope of the disclosure based on experimental data or other optimizations considering the overall economics of the process. Accordingly, it is appropriate that the appended claims are construed broadly and in a manner consistent with the scope of the disclosure.

Claims

1. A reactor system for the conversion of hydrocarbons, the reactor system comprising: a reactor vessel having a reactor wall that defines a reaction chamber, the reaction chamber having a central longitudinal axis, the reactor vessel having an upstream end and a downstream end; a diverging

conduit having an upstream end, a downstream end, and a circumferential wall expanding in width from the upstream end to the downstream end of the diverging conduit, the downstream end of the diverging conduit being in fluid communication with the reaction chamber of the reactor; a feed assembly having an upstream end and a downstream end the downstream end of the feed assembly being operably coupled to the upstream end of the diverging conduit, with the central longitudinal axis passing through the feed assembly, the feed assembly comprising at least two flow inlets, wherein the two flow inlets provide a flow path for at least one each for heated gas and hydrocarbons, respectively; wherein the flow inlets are configured to respectively receive the heated gas and hydrocarbon, and to cause the heated gas and hydrocarbon to mix together to form a swirling mixture as the heated gas and hydrocarbon flow from the feed assembly through the diverging conduit and into the reaction chamber; wherein the flow inlets are configured to receive the heated gas preheated before entering the flow inlets; wherein the reaction chamber is configured such that: the heat required for cracking the hydrocarbon in the reaction chamber primarily comes from the thermal energy in the heated gas, and, the reaction in the reaction chamber creates an exit stream comprising heated gas, hydrocarbon, and reaction products, wherein at least one flow inlet causes its respective feed stream to enter the reactor in a direction that is approximately parallel to the central longitudinal axis, and at least one inlet flow space causes its respective feed stream to enter the reactor in a direction that is approximately perpendicular to the central longitudinal axis, with at least one feed stream having a tangential-to-radial or tangential-to-axial velocity component to form a swirling flow for mixing in the mixing feed streams.

2. The reactor system of claim 1, wherein the feed assembly further comprises guide vanes, the guide vanes being movable to selected positions to provide selected tangential-to-radial or tangential-to-axial velocity ratios of feed streams for mixing in the mixing feed streams.

3. The reactor system of claim 1, wherein the reaction chamber further comprises an outlet, through which the hydrocarbons and reaction products exit the reaction chamber.

4. The reactor system of claim 1, wherein after the heated gas, hydrocarbon and reaction products exit the reaction chamber, the heated gas is separated from the rest of the exit stream.

5. The reactor system of claim 4, wherein the separated heated gas is recycled back to a front of the reactor system.

6. The reactor system of claim 5, further comprising a swirl atomizer configured to induce swirling in the mixing feed streams.

7. The reactor system of claim 1, wherein the heated gas is preheated via renewable energy sources.

8. The reactor system of claim 1, wherein at least one of the flow inlets is an atomizer, the atomizer providing a flow path for the hydrocarbon.

9. The reactor system of claim 8, wherein the hydrocarbons coming in via the atomizer is naphtha, crude oil, pyoil from hydrocarbons, biomass, or plastic waste, or NGL in liquid phase.

10. The reactor system of claim 1, wherein the reaction chamber has an outer wall, and wherein the selection and placement of the one or more flow inlets allows one to control the placement of the hydrocarbon with respect to the heated gas, the placement creating a cooled space in the interior of the reactor.

11. The reactor system of claim 10, wherein the hydrocarbon first enters the reactor closest to the outer wall of the reactor, and then moves radially inward to interact with the heated gas.

12. The reactor system of claim 10, wherein the hydrocarbon first enters the reactor closest to the central longitudinal axis of the reactor, and then moves radially outward to interact with the heated gas.

13. The reactor system of claim 1, wherein the reactor system further comprises a converging conduit, the converging conduit having an upstream and downstream end, the central longitudinal axis passing through the converging conduit, the converging conduit being connected to the upstream end of the diverging conduit, and the upstream end of the feed assembly.

14. The reactor system of claim 13, wherein the converging conduit and the diverging conduit

together comprise a venturi.

15. The reactor system of claim 1, wherein the heated gas is steam.

16. The reactor system of claim 1, wherein the heated gas or the hydrocarbons contain impurities.