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(71) Applicant (for all designated States except US): **MARATHON OIL CANADA CORPORATION** [CA/CA];
Suite 2400, Ernst & Young Tower, 440 Second Avenue
SW, Calgary, Alberta T2P 5E9 (CA).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **SALAZAR-GUILLEN, Jose, Armando** [US/US]; 11290 Messina Way,
Reno, NV 89521 (US). **ARD, Christopher** [US/US]; 107
Curtis Court, Catlettsburg, KY 41129 (US).

(74) Agent: **NIEBERGALL, Shane, M.**; PO Box 8749, Denver, CO 80201 (US).

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(54) Title: HEAVY HYDROCARBON REACTOR

(57) Abstract: A reactor for cracking heavy hydrocarbons includes a tube having an internal passage filled with a fluid that includes heavy hydrocarbon material. The reactor is oriented vertically so that the fluid moves downward through the internal passage of the tube. The internal passage includes alternating linear sections and curved sections. The internal passage is oriented so that it lies on a single plane. The reactor may be combined with another reactor to produce a reactor system.



IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

LETTERS PATENT APPLICATION

HEAVY HYDROCARBON REACTOR

HEAVY HYDROCARBON REACTOR

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

[0001] This patent application claims the benefit of U.S. Provisional Patent Application No. 61/478,252, titled "Heavy Hydrocarbon Reactor," filed on 22 April 2011, the entire contents of which are incorporated by reference herein.

INCORPORATION OF RELATED PATENT APPLICATIONS

[0002] The entire contents of the following documents are incorporated by reference herein: U.S. Pat. App. No. 13/227,470, titled "Nozzle Reactor and Method of Use," filed on 7 September 2011; U.S. Pat. App. No. 12/816,844, titled "Dual Reactor for Better Conversion of Heavy Hydrocarbons," filed on 16 June 2010; U.S. Patent No. 7,618,597, titled "Nozzle Reactor and Method of Use," issued on 17 November 2009 (the '597 patent); and U.S. Patent Application Publication No. 2009/0266741, titled "Nozzle Reactor and Method of Use," published on 29 October 2009 (the '741 publication). In the event of a conflict, the subject matter explicitly recited or shown herein controls over any subject matter incorporated by reference.

BACKGROUND

[0003] Since different crude oils yield different distillation products, oil refining requires balancing product yield with market demand. Balancing these two without manufacturing large quantities of low value fractions requires processes for converting hydrocarbons of one molecular weight range and/or structure into those of another molecular weight range and/or structure. The basic processes for doing this are commonly referred to as cracking processes. This is because the relatively high boiling constituents are cracked, that is, thermally decomposed, into lower molecular weight, smaller, lower boiling molecules.

[0004] Conventional thermal cracking is the thermal decomposition of high molecular weight constituents (higher molecular weight and higher boiling than gasoline constituents) to

form lower molecular weight (and lower boiling) species. Many of these processes use catalysts to crack residual and other heavy feedstocks, alkylation, polymerization, and isomerization. Catalytic cracking is one of the leading processes for upgrading lighter oils (*e.g.*, conventional crude oil) into high quality fuel. Hydrocracking, a catalytic cracking process conducted in the presence of hydrogen, is especially suitable for producing yielding gasoline and/or jet fuels.

[0005] The discovery of huge reserves of heavy oil has attracted renewed interest in thermal cracking processes. Thermal cracking processes such as visbreaking, an abbreviated term for viscosity breaking or viscosity lowering, are used to convert heavy, high viscosity, high boiling hydrocarbons to lower viscosity fractions suitable for further processing or use in heavy fuel oil. These processes may accomplish one or more of the following objectives. First, they reduce the viscosity of the feed stream, which may include heavy hydrocarbon sources such as the residue from distillation operations, the residue from hydroskimming operations, natural bitumen from sources such as tar sands, and even certain high viscosity crude oils. Second, they reduce the amount of residual fuel oil produced in a refinery, which is generally regarded as a low value product. Third, they increase the proportion of middle distillates produced in the refinery. Middle distillates are often used as a diluent for heavy hydrocarbons to lower their viscosity to a marketable level. Cracking the residual hydrocarbons reduces the diluent requirement so that the saved middle distillates can be diverted to higher value products.

[0006] In one example of a process for cracking heavy hydrocarbon material such as those mentioned above, the feed is passed through one or more tubes in a furnace. The heavy hydrocarbon material is heated to a high temperature causing partial vaporization and mild cracking. Conversion is achieved primarily as a result of temperature and residence time, which is why this process is described as being high temperature (*e.g.*, 455 to 510 °C) and short residence time. The short residence time is the principal reason that this is considered a mild thermal reaction. The product that exits the tube is quenched to halt the cracking reactions. This may be done by heat exchange with the feed material, which saves energy, or with a stream of cold material such as gas oil to achieve the same effect.

[0007] These processes extend the boiling range of the heavy hydrocarbon materials so that light and heavy gas oils can be fractionated from the product stream, fed into a catalytic cracking unit, or otherwise processed further as desired. The yield of the various hydrocarbon products depends on the “severity” of the cracking operation as determined by the temperature the feed is heated to in the furnace. At the low end of the scale, a furnace operating at 425 °C would crack only mildly, while operations at 500 °C would be considered as very severe. Arabian light crude residue cracked at 450 °C would yield around 76 wt% tar, 15 wt% middle distillates, 6 wt% gasolines and 3 wt% gas and LPG.

[0008] One problem commonly encountered when cracking heavy hydrocarbon materials is excessive coke formation. As thermal cracking proceeds, reactive unsaturated molecules are formed that continue to react and can ultimately create higher molecular weight species that are relatively hydrogen deficient and readily form coke. The coke is deposited on the cracking equipment and leads to fouling and necessitates frequent cleaning. This is especially a problem in tubular reactors. The coke is deposited in the reaction tubes and eventually fouls or blocks them. Tubular reactors require frequent de-coking, which is labor intensive and can result in substantial downtime.

[0009] Another disadvantage of processes for cracking heavy hydrocarbon material is that, unlike conventional thermal cracking, they do not employ a recycle stream. Conditions are too mild to crack a gas oil recycle stream, and the unconverted heavy hydrocarbon material, if recycled, would cause excessive coking. Further cracking of the residuals must be done in a separate unit that can remove the very heavy fractions that are left.

[0010] Processes for cracking heavy hydrocarbon material also produce a significant amount of gaseous hydrocarbons as a by-product. Although these can be separated for other uses, it is preferable to limit the amount of gases produced to maximize liquid yields.

SUMMARY

[0011] Disclosed below are representative embodiments that are not intended to be limiting in any way. Instead, the present disclosure is directed toward novel and nonobvious features, aspects, and equivalents of the embodiments of the methods described below. The disclosed features and aspects of the embodiments can be used alone or in various novel and nonobvious combinations and sub-combinations with one another.

[0012] A reactor for cracking heavy hydrocarbon material into distillates includes a tube having an internal passage through which the heavy hydrocarbon material passes. The heavy hydrocarbon undergoes cracking reactions as it travels through the reactor thereby producing the distillates. The heavy hydrocarbon can react with a cracking fluid in the reactor that facilitates the cracking reactions.

[0013] The reactor may be oriented vertically so that the fluid in the reactor moves downward through the internal passage. Although the reactor is oriented vertically, the internal passage may lie substantially on a plane so that the reactor appears to be flat. The internal passage may include alternating linear sections and curved sections that form a zig-zag or serpentine shape. The tube can be at least approximately 6 inches in width. In one embodiment, the internal passage has a cylindrical shape and its diameter is at least approximately 6 inches.

[0014] The reactor can be used as part of a method for cracking the heavy hydrocarbon material and forming distillates. The method includes reacting the heavy hydrocarbon material with a cracking fluid such as steam or natural gas in the reactor. The temperature and residence time of the heavy hydrocarbon material is sufficient to convert a substantial amount of it to distillates. The residence time and linear velocity of the fluid in the reactor may be approximately 0.05 s to 1.5 s and approximately 4 to 40 m/s, respectively.

[0015] In one embodiment, the reactor is part of a multiple reactor system for cracking heavy hydrocarbon material. The reactor is the second reactor in the system and is positioned in series after a first reactor. The heavy hydrocarbon material begins to crack in the first reactor into

lighter hydrocarbon material. The second reactor provides the residence time at high temperature that further drives conversion of the heavy hydrocarbon material into distillates.

[0016] The first reactor may be a nozzle reactor. The cracking fluid is accelerated to supersonic speed in the nozzle reactor and mixed with the heavy hydrocarbon material in the feed to initiate cracking. The cracking fluid functions as a hydrogen source thereby minimizing coke formation due to excessive hydrogen loss from the heavy hydrocarbon material.

[0017] The effluent from the second reactor is separated to isolate any remaining heavy hydrocarbon material. The heavy hydrocarbon material may be recycled back to the first reactor until it is completely eliminated. The recycled heavy hydrocarbon material does not produce significant amounts of coke due to the hydrogen rich environment supplied by the cracking fluid. The entire process may be operated without the use of a catalyst or added hydrogen.

[0018] In one embodiment, the raw feed is combined with the effluent from the second reactor and separated into distillates and heavy hydrocarbon material. Any suitable separation process may be used such as distillation. The distillates continue on to further processing and the heavy hydrocarbon material is fed into the reactor system. This design allows the distillates from the feed and the reactor effluent to be separated in a single step with the same separation unit. It also increases the concentration of heavy hydrocarbon material in the feed to the reactor system.

[0019] In another embodiment, the raw feed may be fed directly into the reactor system before being separated into its constituent fractions. For example, this may be desirable when the raw feed is largely made up of heavy hydrocarbon material. A variety of other configurations may also be used. For example, the raw feed may be separated in a first separation unit, the heavy hydrocarbon material fed into the reactor system, and the effluent separated in a second separation unit.

[0020] The term "heavy hydrocarbon material" is used to refer to the hydrocarbon fraction that has a boiling point at or above 525 °C. This material may be obtained from a number of sources such as the residue from distillation operations such as atmospheric or vacuum

distillation, the residue from hydroskimming operations, natural sources such as tar sands (including oil sands and oil shale), and even certain high viscosity crude oils. The term “distillates” is used to refer to the hydrocarbon fraction that has a boiling point below 525 °C. The term “coke precursor” is used to refer to carbon based material that is not soluble in toluene. It should be appreciated that all pressures are given as gauge pressures unless noted otherwise.

[0021] The foregoing and other features, utilities, and advantages of the subject matter described herein will be apparent from the following more particular description of certain embodiments as illustrated in the accompanying drawings. In this regard, it is be understood that the scope of the invention is to be determined by the claims as issued and not by whether any given subject matter includes any or all features or aspects noted in this Summary or addresses any issues noted in the Background.

DRAWINGS

[0022] The preferred and other embodiments are disclosed in association with the accompanying drawings in which:

[0023] Figure 1 is a schematic representation of one embodiment of a system for cracking heavy hydrocarbon material.

[0024] Figure 2 is a schematic representation of another embodiment of a system for cracking heavy hydrocarbon material that includes recycle of unconverted heavy hydrocarbon material.

[0025] Figure 3 shows one embodiment of a nozzle reactor that may be used in the process.

[0026] Figure 4 shows one embodiment of a nozzle reactor coupled in series to a coil reactor.

[0027] Figure 5 shows one embodiment of a nozzle reactor coupled in series to a tubular reactor.

[0028] Figures 6 and 7 shows different embodiments of a tubular reactor having a serpentine shape.

[0029] Figure 8 shows an exemplary embodiment of a method for cracking heavy hydrocarbon material.

DETAILED DESCRIPTION

[0030] An improved process for cracking or upgrading heavy hydrocarbon material is described herein. Although the process is described primarily in the context of upgrading heavy hydrocarbon materials, it should be appreciated that the referenced process, concepts, and features may be used in a variety of other settings that would be recognized by those of ordinary skill in the art (e.g., upgrading distillates). Also, it should be understood, that the features, advantages, characteristics, etc. of one embodiment may be applied to any other embodiment to form an additional embodiment unless noted otherwise.

[0031] Figure 1 shows one embodiment of a system 100 for cracking heavy hydrocarbon material. The system includes a first reactor 102 and a second reactor 104 positioned in series. The first reactor 102 partially upgrades the heavy hydrocarbon material and the second reactor 104 further upgrades it until it reaches the overall desired conversion level. The second reactor 104 discharges an upgraded effluent material 110.

[0032] A feed 106 includes heavy hydrocarbon material and is fed into the first reactor 102. A cracking fluid 108 is also fed into the first reactor. Although the feed 106 may enter the first reactor 102 without being separated, it is often desirable to separate the heavy hydrocarbon material before it enters the first reactor 102 to prevent eliminate or reduce the amount of distillates present in the feed 106.

[0033] The feed 106 may come from a variety of sources. Examples of suitable sources include the residual fraction of distillation operations such as atmospheric or vacuum distillation or from the residual fraction of hydroskimming operations. Other sources include natural sources such as oil sands (which includes tar sands, oil shale, etc.) or even certain high viscosity crude

oils. The concentration of heavy hydrocarbon material in the feed 106 varies depending on its source and whether it was processed previously.

[0034] The composition of the feed 106 can vary widely, but often includes asphaltenes, resins, aromatic hydrocarbons, and alkanes in varying amounts. Asphaltenes are large polycyclic molecules that are commonly defined as those molecules that are insoluble in n-heptane and soluble in toluene. Resins are also polycyclic but have a lower molecular weight than asphaltenes. Aromatic hydrocarbons are derivatives of benzene, toluene and xylene. The feed may also include 12 to 25 wt% micro carbon as determined using ASTM D4530-07.

[0035] The feed 106 can include heavy hydrocarbon material and other lower boiling fractions. In most situations, it is advantageous to separate distillates from the feed 106 so that it is composed entirely or almost entirely of heavy hydrocarbon material when it enters the first reactor 102. Any suitable separation process (e.g., distillation, etc.) may be used to separate the distillates. In one embodiment, the feed 106 includes at least approximately 95 wt% heavy hydrocarbon material, at least approximately 98 wt% heavy hydrocarbon material, or, desirably, at least approximately 99 wt% heavy hydrocarbon material. It should be appreciated that in other embodiments, the feed 106 may include a substantial amount of distillates.

[0036] The feed 106 is preheated before it enters the nozzle reactor to a temperature that is just below the temperature at which cracking occurs. This imparts the maximum amount of energy to the feed 106 without initiating cracking. In one embodiment, the feed 106 may be heated to a temperature that is no more than 400 °C. In another embodiment, the feed 106 may be heated to at least approximately 350 °C. In yet another embodiment, the feed 106 may be heated to approximately 350 °C to 400 °C.

[0037] The cracking fluid 108 may be any material that when combined with the feed 106 in the first reactor 102 and the second reactor 104 cracks the heavy hydrocarbon material and/or serves as a hydrogen donor to the heavy hydrocarbon material. The cracking fluid 108 may be supplied as a superheated fluid. Suitable cracking fluids include steam, natural gas, methanol,

ethanol, ethane, propane, other gases, or combinations thereof. In one embodiment, the cracking fluid 108 is superheated steam, natural gas, or a combination of both.

[0038] The cracking fluid 108 may help to prevent the formation of coke in the system 100 by functioning as a hydrogen donor in the cracking reactions. The hydrogen from the cracking fluid 108 is transferred to the heaviest hydrocarbons thereby preventing them from becoming hydrogen depleted in the extreme conditions of the reactors 102, 104.

[0039] The cracking fluid 108 may be heated and pressurized before it is introduced to the first reactor 102. The heat and pressure give the cracking fluid 108 added energy that is transferred to the heavy hydrocarbon material causing it to crack or scission. The cracking fluid 108 may be provided in an amount and at a temperature sufficient to heat the feed 106 to the desired temperature and initiate the cracking reactions. The amount of heat supplied in the cracking fluid 108 may be determined using a mass and energy balance.

[0040] In one embodiment, the cracking fluid 108 is supplied at a temperature of at least approximately 550 °C or at least approximately 600 °C. In another embodiment, the cracking fluid 108 is supplied at a temperature of approximately 550 °C to 700 °C or approximately 600 °C to 650 °C. In yet another embodiment, the cracking fluid 108 is supplied at a temperature of no more than approximately 700 °C.

[0041] In one embodiment, the cracking fluid 108 is pressurized to at least approximately 1380 kPa or at least approximately 3100 kPa. In another embodiment, the cracking fluid 108 is pressurized to approximately 1380 kPa to 6200 kPa or approximately 3100 kPa to 5170 kPa. In yet another embodiment, the cracking fluid 108 is pressurized no more than approximately 6200 kPa or no more than approximately 5170 °C.

[0042] The ratio of cracking fluid 108 to feed 106 supplied to the first reactor 102 varies depending on a number of factors. In general, it is desirable to minimize the amount of cracking fluid 108 to reduce cost while still successfully cracking the heavy hydrocarbons. In one embodiment, the ratio of cracking fluid 108 to feed 106 is no more than 2.0 or no more than 1.7.

In another embodiment, the ratio of cracking fluid 108 to feed 106 may be approximately 0.5 to 2.0 or approximately 1.0 to 1.7. In yet another embodiment, the ratio of cracking fluid 108 to feed 106 is at least approximately 0.5 or at least approximately 1.0

[0043] It should be appreciated that the first reactor 102 may be any suitable reactor capable of at least partially upgrading heavy hydrocarbon material. In one embodiment, the first reactor 102 is a nozzle reactor. A nozzle reactor includes any type of apparatus having a convergent and/or divergent internal shape in which one or more materials are injected for the purpose of chemically and/or mechanically interacting with each other. Any of the nozzle reactors disclosed in the documents incorporated by reference can be used.

[0044] In one embodiment, the nozzle reactor includes a first entry opening that receives the cracking fluid, a second entry opening that receives the feed, and an exit opening. The first entry opening, the second entry opening, and the exit opening are in fluid communication with each other. This can be accomplished in any of a number of ways. For example, the first entry opening can lead to a first input passage or injection passage. The second entry opening can intersect and/or be combined with the first input passage and then lead to the exit opening.

[0045] The first input passage is shaped to accelerate the cracking fluid. The first input passage may have any suitable geometry that is capable of doing this. In one embodiment, the first input passage includes a convergent section where the passage narrows from a wide diameter to a smaller diameter in the direction of the flow. In another embodiment, the first input passage includes a divergent section where the passage expands from a smaller diameter to a larger diameter in the direction of the flow. In yet another embodiment, the first input passage includes a convergent section followed by a divergent section. The first input passage appears to be pinched in the middle, making a carefully balanced, asymmetric hourglass-shape. This configuration is commonly referred to as convergent-divergent nozzle or "con-di nozzle".

[0046] The convergent section of the first input passage accelerates subsonic fluids since the mass flow rate is constant and the material must accelerate to pass through the smaller opening.

The flow will reach sonic velocity at the narrowest point (i.e., the nozzle throat) provided that the nozzle pressure ratio is high enough. In this situation, the first input passage is said to be choked.

[0047] Increasing the nozzle pressure ratio further does not increase the Mach number at the throat beyond unity. However, the flow downstream from the nozzle is free to expand and can reach supersonic velocities. It should be noted that Mach 1 can be a very high speed for a hot fluid since the speed of sound varies as the square root of absolute temperature. Thus the speed reached at the nozzle throat can be far higher than the speed of sound at sea level.

[0048] The divergent section of the first input passage slows subsonic fluids, but accelerates sonic or supersonic fluids. A convergent-divergent geometry can therefore accelerate fluids that have choked in the convergent section to supersonic speeds. The convergent-divergent geometry can be used to accelerate the hot, pressurized cracking fluid to supersonic speeds, and upon expansion, to shape the exhaust flow so that the heat energy propelling the flow is maximally converted into kinetic energy.

[0049] The flow rate of the fluid through the convergent-divergent nozzle is isentropic (fluid entropy is nearly constant). At subsonic flow the fluid is compressible so that sound, a small pressure wave, can propagate through it. At the "throat", where the cross sectional area is a minimum, the fluid velocity locally becomes sonic (Mach number = 1.0). As the cross sectional area increases the gas begins to expand and the gas flow increases to supersonic velocities where a sound wave cannot propagate backwards through the gas as viewed in the frame of reference of the nozzle (Mach number > 1.0).

[0050] The first input passage will only choke at the throat if the pressure and mass flow rate is sufficient to reach sonic speeds, otherwise supersonic flow is not achieved and the first input passage will act as a Venturi tube. In order to achieve supersonic flow, the entry pressure to the nozzle should be significantly above ambient pressure.

[0051] The pressure of the gas at the exit of the expansion portion of the first input passage can be low, but should not be too low. The exit pressure can be significantly below ambient

pressure since pressure cannot travel upstream through the supersonic flow. However, if the pressure is too far below ambient, then the flow will cease to be supersonic or the flow will separate within the expansion portion of the nozzle forming an unstable jet that may “flop” around within the nozzle. In one embodiment, the ambient pressure is no higher than approximately 2-3 times the pressure in the supersonic gas at the exit.

[0052] The supersonic flow collides and mixes with the heavy hydrocarbon material in the nozzle reactor. In this way, the nozzle reactor generates a tremendous amount of thermal and kinetic energy that is used to crack the heavy hydrocarbon material.

[0053] In one embodiment, the nozzle reactor is configured to accelerate the cracking fluid to at least approximately Mach 1, at least approximately Mach 1.5, or, desirably, at least approximately Mach 2. In another embodiment, the nozzle reactor accelerates the cracking fluid to approximately Mach 1 to 7, approximately Mach 1.5 to 6, or, desirably, approximately Mach 2 to 5.

[0054] The cracking produced in the nozzle reactor is influenced by a number of factors such as temperature, residence time, pressure, and impact force. Without wishing to be bound by theory, it appears that the mechanical forces exerted on the heavy hydrocarbon material due to the impact of the cracking fluid are a significant factor in the success of the system 100. The impact force directly cleaves the molecule apart and/or weakens it making it more susceptible to chemical attack.

[0055] In one embodiment, the nozzle reactor is the same or substantially similar to the nozzle reactor disclosed in the '597 patent or the '741 publication. The nozzle reactor includes an interior reactor chamber, a first input passage or injection passage, and a second input passage or material feed passage. The interior reactor chamber has an injection end and an ejection end. The first input passage is positioned in fluid communication with the injection end of the interior reactor chamber.

[0056] The first input passage is roughly shaped like an hourglass with enlarged openings at the entrance (the enlarged volume injection section) and exit (the enlarged volume ejection section) and a constricted or narrow section in the middle. The cracking fluid 108 enters the nozzle reactor through the first input passage. The cracking fluid 108 enters the first input passage at a material injection end and exits the passage at a material ejection end. The first input passage opens to the interior reactor chamber.

[0057] The heavy hydrocarbon material enters the nozzle reactor through the second input passage, which is in fluid communication with the interior reactor chamber and is generally located adjacent to the location where the cracking fluid 108 exits the first input passage. Additionally, the second input passage is positioned transverse to the direction of the first input passage.

[0058] Turning to Figure 3, an exemplary embodiment of a nozzle reactor 10 is shown. The nozzle reactor 10 has a reactor body injection end 12, a reactor body 14 extending from the reactor body injection end 12, and an ejection port 13 in the reactor body 14 opposite its injection end 12. The reactor body injection end 12 includes a first input passage 15 extending into the interior reactor chamber 16 of the reactor body 14. The central axis A of the first input passage 15 is coaxial with the central axis B of the interior reactor chamber 16.

[0059] The first input passage 15 has a circular diametric cross-section and, as shown in the axially-extending cross-sectional view of Figure 3, opposing inwardly curved side wall portions 17, 19 (i.e., curved inwardly toward the central axis A of the first input passage 15) extending along the axial length of the first input passage 15. In certain embodiments, the axially inwardly curved side wall portions 17, 19 of the first input passage 15 facilitate high speed injection of the cracking fluid 108 as it passes through the first input passage 15 into the interior reactor chamber 16. The curved side wall portions 17, 19 also form convergent-divergent sections in the first input passage 15.

[0060] The side wall of the first input passage 15 can provide one or more of the following:
(i) uniform axial acceleration of the cracking fluid 108 passing through the first input passage 15;

(ii) minimal radial acceleration of such material; (iii) a smooth finish; (iv) absence of sharp edges; and (v) absence of sudden or sharp changes in direction. The side wall configuration can render the first input passage 15 substantially isentropic.

[0061] A second input passage 18 extends from the exterior of the reactor body 14 toward the interior reaction chamber 16 transversely to the axis B of the interior reactor chamber 16. The second input passage 18 penetrates an annular feed port 20 adjacent the interior reactor chamber wall 22 at the interior reactor chamber injection end 24 abutting the reactor body injection end 12.

[0062] The feed port 20 includes an annular, radially extending reactor chamber feed slot 26 in fluid communication with the interior reactor chamber 16. The feed port 20 is thus configured to inject the feed 106: (i) at about a 90° angle to the axis of travel of the cracking fluid 108 injected from the first input passage 15; (ii) around the entire circumference of a cracking fluid 108 injected through the first input passage 15; and (iii) to impact the entire circumference of the cracking fluid stream virtually immediately upon its emission from the first input passage 15 into the interior reactor chamber 16.

[0063] The annular feed port 20 may have a U-shaped or C-shaped cross-section among others. In certain embodiments, the annular feed port 20 may be open to the interior reactor chamber 16, with no arms or barrier in the path of fluid flow from the second input passage 18 toward the interior reactor chamber 16. The junction of the annular feed port 20 and the second input passage 18 can have a radiused cross-section.

[0064] The interior reactor chamber 16 may be bounded by stepped, telescoping side walls 28, 30, 32 extending along the axial length of the reactor body 14. In certain embodiments, the stepped side walls 28, 30, 32 are configured to: (i) allow a free jet of injected cracking fluid 108 to travel generally along and within the conical jet path C generated by the first input passage 15 along the axis B of the interior reactor chamber 16, while (ii) reducing the size or involvement of back flow areas (e.g., 34, 36) outside the conical or expanding jet path C, thereby forcing

increased contact between the high speed cracking fluid stream within the conical jet path C and the feed 106 injected through the annular feed port 20.

[0065] As indicated by the drawing gaps 38, 40 in the embodiment of Figure 3, the reactor body 14 has an axial length (along axis B) that is much greater than its width. In the embodiment shown in Figure 3, exemplary length-to-width ratios are typically in the range of 2 to 7 or more.

[0066] The dimensions of the various components of the nozzle reactor shown in Figure 3 are not limited, and may generally be adjusted based on the amount of feed flow rate. Table 1 provides exemplary dimensions for the various components of the nozzle reactor 10 based on the hydrocarbon input in barrels per day (BPD).

Table 1: Exemplary nozzle reactor specifications

Nozzle Reactor Component (mm)	Feed Input (BPD)		
	5,000	10,000	20,000
First input passage entrance section diameter	148	207	295
First input passage mid-section diameter	50	70	101
First input passage exit section diameter	105	147	210
First input passage length	600	840	1,200
Interior reaction chamber injection end diameter	187	262	375
Interior reaction chamber ejection end diameter	1,231	1,435	1,821
Interior reaction chamber length	640	7,160	8,800
Overall nozzle reactor length	7,000	8,000	10,000
Overall nozzle reactor outside diameter	1,300	1,600	2,000
Overall nozzle reactor length to outside diameter ratio	5.4	5.0	5.0

[0067] The use of the nozzle reactor 10 to crack the heavy hydrocarbon material is described in greater detail. The feed 106, which includes the heavy hydrocarbon material, is injected into the interior reactor chamber 16 via the second input passage 18. The feed 106 may be pretreated

prior to entering the nozzle reactor 10 to alter the amount or fraction of heavy hydrocarbon material. The feed 106 may also be pretreated to alter other characteristics of the feed.

[0068] In one embodiment, the feed 106 includes the heavy fraction from a separation unit. For example, a raw feed may be separated using a distillation column and the heavy fraction sent to the nozzle reactor 10. The effluent produced by the nozzle reactor 10 and/or the second reactor 104 can be added to the raw feed and separated from any remaining heavy hydrocarbon material in the same separation unit used to provide the feed 106.

[0069] The feed 106 and the cracking fluid 108 are simultaneously injected into the interior reactor chamber 16 through the second input passage 18 and the first input passage 15. The configuration of the first input passage 15 is such that the cracking fluid 108 is accelerated to supersonic speed and enters the interior reactor chamber 16 at supersonic speed. The cracking fluid 108 produces shock waves that facilitate mechanical and chemical scission of the heavy hydrocarbon material. In this manner, the heavy hydrocarbon material may be broken down into distillates.

[0070] The nozzle reactor's conversion rate of heavy hydrocarbon material into distillates varies depending on the inputs, conditions, and a number of other factors. In one embodiment, the conversion rate of the nozzle reactor 10 is at least approximately 2%, at least approximately 4%, or, desirably, at least approximately 8%. In another embodiment, the conversion rate of the nozzle reactor 10 is approximately 2% to 25%, approximately 4% to 20%, or, desirably, approximately 8% to 16%.

[0071] It should be appreciated that the second reactor 104 may be any suitable reactor capable of further upgrading the heavy hydrocarbon material. In one embodiment, the second reactor 104 is a tubular reactor. The tubular reactor provides sufficient residence time at high temperature and high velocity to provide the overall desired level of conversion of heavy hydrocarbon material. The tubular reactor includes a tube or pipe having an internal passage that generally has a uniform cross-sectional shape and may be linear or non-linear.

[0072] Figure 4 shows one embodiment of a reactor system 11 that includes the first reactor 10 and a tubular reactor 112 is a coiled shape. The reactor 112 is one example of a non-linear tubular reactor. The non-linear shape of the reactor 112 forces the material to repeatedly change direction as it passes through the tube. This causes greater mixing and faster reaction time between the heavy hydrocarbon material and the cracking fluid 108.

[0073] The coil configuration affects the temperature and pressure distribution as well as the product yields. The reactor 112 is spiral shaped, but it should be appreciated that the reactor 112 may have any suitable non-linear shape. Other suitable shapes include a single row, split, reversed split, etc. Coil reactors typically increase the rate of conversion of heavy hydrocarbon materials as well as the amount converted.

[0074] As shown in Figure 4, the feed 106 and cracking fluid 108 pass directly from the nozzle reactor 10 to the reactor 112. This quick transition allows the materials to enter the reactor 112 without losing too much heat or velocity. It should be appreciated, however, that the materials may undergo some form of processing or treatment after leaving the nozzle reactor 10 but before entering the reactor 112.

[0075] Figure 5 shows another embodiment of a reactor system 13 including the nozzle reactor 10 and another embodiment of a tubular reactor 50. In this embodiment, the tubular reactor 50 has a roughly serpentine shape. The reactor 50 is positioned immediately following the nozzle reactor 10. The mixture of the feed 106 and the cracking fluid 108 exits the nozzle reactor 10 and immediately enters the reactor 50. The reactor 50 provides the residence time at high temperature that allows the cracking process to continue until the desired conversion level is reached.

[0076] The reactor 50 includes a tube having an internal passage 52. The reactor 50 is oriented vertically so that the effluent from the nozzle reactor 10 moves downward through the reactor 50. Gravity helps to maintain the desired flow rate and velocity in the reactor 50. The internal passage includes alternating linear sections 54 and curved sections 56. The sections 54, 56 are oriented in a single plane so that the reactor 50 is roughly flat. In this way, the reactor 50

can be positioned vertically in a plant type environment without taking up a lot of space. In one embodiment, the internal passage includes at least three, four, or five alternating linear sections 54 and curved sections 56.

[0077] The linear sections 54 slope downward in the direction of fluid flow. The curved sections 56 curve less than a full 180° to provide the linear sections 54 with a downward slope. In one embodiment, the curved sections curve approximately 150° up to 180° or approximately 170° to 180° . The linear sections 54 may be any suitable length. In one embodiment, the linear sections 54 are approximately 3 to 10 feet in length.

[0078] The internal passage 52 may have any suitable shape or configuration. In one embodiment, the tube is a round pipe so that the internal passage 52 has a cylindrical shape and a circular cross sectional shape. In other embodiments, the internal passage 52 may have different cross-sectional shapes such as square or rectangular.

[0079] The reactor 50 may be relatively large to provide a high amount of throughput. In one embodiment, the internal passage 52 is at least approximately 6 inches wide, at least approximately 9 inches wide, at least approximately 12 inches wide, or at least approximately 15 inches wide. The width of the internal passage 52 should be measured at its widest point for non-circular cross sectional shapes. If the internal passage 52 is circular, then the width is the diameter.

[0080] The height of the reactor 50 and the length of the linear sections 54 may be closely related. As shown in Figure 6, the length L_1 of the linear sections 54 is approximately 5 feet and the height of the reactor 50 is approximately 24 feet. In contrast, the Length L_2 of the linear sections 54 in Figure 7 is approximately 7 feet and the height is approximately 13.5 feet. In these examples, the height of the reactor 50 increases as the length of the linear sections 54 is shortened. In one embodiment, the reactor 50 is at least approximately 10 feet high, at least approximately 20 feet high, or at least approximately 60 feet high.

[0081] The heavy hydrocarbon material is maintained at a temperature in the tubular reactor that is high enough to effectively crack it, but not high enough to cause excessive coking. In one embodiment, the temperature is at least approximately 410 °C or at least approximately 430 °C. In another embodiment, the temperature is approximately 410 °C to 490 °C or approximately 430 °C to 460 °C. In yet another embodiment, the temperature is no more than approximately 490 °C or no more than approximately 480 °C.

[0082] In most situations it is not necessary to heat the tubular reactor. Large scale implementations do not require additional heat since the energy imparted to the feed 106 and the cracking fluid 108 before entering the system 100 is sufficient to achieve the desired conversion. However, if the material throughput is small relative to the size of the reactor tube, energy losses such as heat losses may be more acute. In these circumstances, it may be desirable to heat the reactor tube to maintain the desired conversion and/or product yields.

[0083] The residence time and linear velocity of the heavy hydrocarbon material in the tubular reactor may be adjusted as necessary to provide the desired conversion rate and product characteristics. In one embodiment, the residence time is at least approximately 0.05 s, at least approximately 0.10 s, or, desirably, at least approximately 0.15 s. In another embodiment, the residence time is approximately 0.05 s to 1.5 s, approximately 0.10 s to 1.4 s, or, desirably, approximately 0.15 s to 1.3 s. In yet another embodiment, the residence time is no more than approximately 2 s, no more than approximately 1.5 s, no more than approximately 1.4 s, or, desirably, no more than approximately 1.3 s.

[0084] The linear velocity of the heavy hydrocarbon material in the tubular reactor may be at least approximately 4 m/s, at least approximately 5 m/s, or, desirably, at least approximately 6 m/s. In another embodiment, the linear velocity is approximately 4 to 40 m/s, approximately 5 to 35 m/s, or, desirably 4 to 32 m/s. In yet another embodiment, the linear velocity is no more than approximately 40 m/s, no more than approximately 35 m/s, or, desirably, no more than approximately 32 m/s.

[0085] The pressure gauge in the tubular reactor may vary as required to sustain the cracking reactors. In one embodiment, the tubular reactor may be at a pressure of approximately -34 kPa to 240 kPa or approximately -34 kPa to 140 kPa.

[0086] Although the tubular reactor has been described primarily in conjunction with another reactor, it should be appreciated that the tubular reactor can be used along without any other reactors. The tubular reactor may be made of any suitable material such as metal, composites, and so forth. In one embodiment, the tubular reactor is made of SS-316.

[0087] The system 100 cracks the heavy hydrocarbon material to produce lighter, lower molecular weight hydrocarbons. In one embodiment, the heavy hydrocarbon material is broken down into light hydrocarbon liquid distillate. The light hydrocarbon liquid distillate includes hydrocarbons having a molecular weight less than about 300 Daltons. In certain embodiments, about 25% to about 50% of the heavy hydrocarbon material cracked in the system 100 is converted into distillates.

[0088] The system 100 may provide a much higher conversion rate than other comparable systems. The conversion rate of heavy hydrocarbon material into distillates in the system 100 varies depending on the inputs, conditions, and a number of other factors. In one embodiment, the conversion rate of the system 100 is at least approximately 15%, at least approximately 30%, or, desirably, at least approximately 35%.

[0089] The total residence time of the heavy hydrocarbon material in the nozzle reactor and the tubular reactor may vary widely. In one embodiment, the total residence time is at least approximately 0.2 s or at least approximately 0.3 s. In another embodiment, the total residence time is approximately 0.2 s to 2 s or approximately 0.3 s to 1.2 s. In yet another embodiment, the residence time is no more than approximately 2 s or no more than approximately 1.8 s.

[0090] As already mentioned above, one significant advantage of the system 100 is that it produces very little, if any, coke and minimizes the amount of gas generated. This makes it possible to operate the system 100 for long periods of time without cleaning. In one embodiment,

the system 100 may be operated indefinitely. Minimizing coke production also means that more of the heavy hydrocarbon material is conserved so that it can be used to produce higher value products than coke.

[0091] The amount of coke produced by the system 100 can be determined by measuring the amount of coke precursors present in the feed 106 and the effluent 110. For example, the feed 106 may include 0.1 wt% to 0.2 wt% of coke precursors and the effluent 120 may include 1 wt% to 2 wt% of coke precursors. This represents a substantial improvement over other technologies. In one embodiment, the effluent 110 may include no more than 5 wt% of coke precursors or no more than 3 wt% of coke precursors.

[0092] Conventional systems for processing heavy hydrocarbon material increase the amount of micro carbon in the feed. The amount of micro carbon in the feed may be considered a proxy for determining how much coke is produced in some situations. The system 100 reduces the amount of micro carbon present. The amount of micro carbon present in the effluent 110 is less than in the feed 106. This is another indication that the system 100 is producing favorable results.

[0093] It should be appreciated that some portion of heavy hydrocarbon material may pass through the system 100 without being cracked. This material may be referred to as non-participating heavy hydrocarbons or uncracked heavy hydrocarbons, since the reactors 102, 104 did not act on this material to crack it into lighter hydrocarbons. Heavy hydrocarbon material that is cracked but still qualifies as heavy hydrocarbon material may also be referred to as non-participating heavy hydrocarbons.

[0094] The effluent 110 from the system 100 may be transported to a separation unit that separates it into its constituent fractions. The separation unit may be any suitable separator capable of separating the effluent 110. Examples of suitable separation units include, but are not limited to, atmospheric or vacuum distillation units, gravity separation units, filtration units, and cyclonic separation units.

[0095] The non-participating hydrocarbons may be subjected to further processing to upgrade it into more useful material. Various types of processing may be performed on the non-participating hydrocarbon for upgrading the non-participating hydrocarbon. The remaining fractions may be used as end products or be subjected to further processing.

[0096] Depending on the situation, it may not be necessary to crack all of the heavy hydrocarbon material in the feed 106. It may only be necessary to upgrade a portion of the heavy hydrocarbon material to produce stable products such as synthetic crude oil, which can include some amount of heavy hydrocarbon material.

[0097] Turning to Figure 2, another embodiment of a system 150 for cracking heavy hydrocarbon material is shown. The system 150 is similar to the system 100 except that the non-participating heavy hydrocarbons 152 are separated from the effluent 110 in separation unit 154 and recycled back to the first reactor 102. In one embodiment, the non-participating heavy hydrocarbons 152 can be recycled back in perpetuity because the hydrogen interaction with the cracking fluid 108 minimizes or prevents coke formation. In another embodiment, no more than approximately 10 wt% (or 0 to 10 wt%) of the heavy hydrocarbons 152 are purged to increase process reliability and maintain a constant concentration of contaminants such as metals and sulfur in the material being recycled.

[0098] The system 150 may provide a significantly higher conversion rate than other comparable systems including hydrocrackers. The conversion rate of heavy hydrocarbon material into distillates in the system 150 varies depending on the inputs, conditions, and a number of other factors. In one embodiment, the conversion rate of heavy hydrocarbon material in the system 150 may be at least approximately 65%, at least approximately 75%, or, desirably, at least approximately 90%. In another embodiment, most or at least substantially all of the heavy hydrocarbon material that enters the system 150 is cracked to distillates. The amount of non-participating heavy hydrocarbon material and/or coke left over from the process may be minor.

[0099] In another embodiment, the system 150 is similar to the system shown in Figure 2 except that the feed 106 is a raw feed and it enters the separation unit 154 without entering the reactors 102, 104. The feed 106 may be combined with the effluent 110 before entering the separation unit 154 or the feed 106 and the effluent 110 may separately enter the separation unit 154. The heavy hydrocarbon material is separated from the feed 106 and the effluent 10 and fed back to the first reactor 102 in the manner shown in Figure 2.

[0100] In another embodiment, the non-participating hydrocarbons may be injected into a third and fourth reactor positioned in series. The third reactor may be a nozzle reactor that is designed similarly or identical to the first nozzle reactor. The fourth reactor may be a tubular reactor that is similar or identical to the second reactor. The dimensions of the additional nozzle and tubular reactor may be identical to the dimensions of the first nozzle and tubular reactor, or they may be scaled up or down. The non-participating hydrocarbon stream may also be pretreated before entering the third and fourth reactor in a similar or identical way as those described above.

[0101] It should be noted that the systems 100, 150 crack the heavy hydrocarbon material without the use of a catalyst or added elemental hydrogen. Thus, the systems 100, 150 are not catalytic cracking processes or hydro-cracking processes.

[0102] A method 210 for cracking heavy hydrocarbon material is depicted in Figure 5. The method includes the step 200 of reacting the heavy hydrocarbon material and the cracking fluid 108 in the first reactor 102 to form a first effluent material. At step 202, the first effluent material is reacted in the second reactor 104 to form a second effluent material. In one embodiment, the first effluent is discharged directly from the first reactor 102 to the second reactor 104 without undergoing any intermediate processing or storage.

[0103] The second effluent material is separated at step 204 to isolate the non-participating heavy hydrocarbon material from distillates 212 and gas 214. The non-participating heavy hydrocarbon material 152 is then recycled back to the first reactor 102. In some embodiments the

separation and recycling step may be skipped in favor of sending the effluent on for further processing (e.g., catalytic cracking, hydro-cracking, etc.).

Examples

[0104] The following examples are provided to further illustrate the subject matter disclosed herein. These examples should not be considered as limiting or restricting the claimed subject matter in any way.

Example 1

[0105] This example compares the conversion of heavy hydrocarbon material in a nozzle and coil reactor versus a nozzle reactor alone. The hydrocarbon material used in this example is Cold Lake raw bitumen and it has the properties shown in Table 2. The cracking fluid is steam.

Table 2: Feed hydrocarbon material

Hydrocarbon material properties	
API	10.4
Sulfur (wt%)	4.8
Micro carbon (wt%)	16.9
Heavy hydrocarbon material (wt%)	59.2

[0106] The nozzle reactor is substantially the same as the nozzle reactor shown and described in U.S. Patent Application Publication No. 2009/0266741. The specifications of the nozzle reactor are given in Table 3. The coil reactor is a 2194.4 cm long tube that has an internal diameter of 1.6 cm that is uniform throughout its entire length. The coil reactor has a spiral shape.

Table 3: Nozzle reactor specifications

Nozzle Reactor Component	Size (mm)
First input passage injection section diameter	3.0
First input passage mid-section diameter	1.3
First input passage ejection section diameter	2.26
First input passage length	20
Interior reaction chamber injection end diameter	3.7
Interior reaction chamber ejection end diameter	16
Interior coil reactor length	21944
Overall length of nozzle and coil reactor	21964
Overall nozzle reactor outside diameter	19

[0107] Each run is conducted as follows. The cracking fluid is superheated to approximately 650 °C and approximately 2000 kPa. The cracking fluid is sent to the nozzle reactor where it reaches a supersonic velocity of approximately Mach 2.8.

[0108] The heavy hydrocarbon material is preheated to a temperature of approximately 380 °C and injected into the nozzle reactor where it reacts with the superheated cracking fluid. The nozzle reactor converts part of the heavy hydrocarbon material into lighter hydrocarbons that have a boiling point below 525 °C.

[0109] The partially upgraded feed from the nozzle reactor is discharged to the coil reactor. The coil reactor provides the residence time at cracking temperatures of 420 to 470 °C to further convert the heavy hydrocarbon material into lighter distillates.

[0110] Four runs are performed with the first run serving as a control since only the nozzle reactor was used. A recycle stream was not used in any of the runs. Table 4 shows the characteristics and results of each run.

Table 4: Conversion effectiveness of nozzle and coil reactor combination

Sample	Reactor Type	Coil Reactor Residence Time (s)	Conversion* (%)	Distillates** Produced (vol %)
N1	Nozzle only	NA	4.6	4.9
NC1	Nozzle and Coil Reactor	0.15	16.1	16.0
NC2	Nozzle and Coil Reactor	0.3	20.7	19.3
NC3	Nozzle and Coil Reactor	0.6	30.3	29.2

* Conversion refers to the amount of heavy hydrocarbon material converted to distillates.

[0082] This example demonstrates that the coil reactor increases the conversion of the heavy hydrocarbon material versus the nozzle reactor alone. The coil reactor provides increased residence time at high temperature, which drives conversion of the heavy hydrocarbon material.

Example 2

[0111] This example compares the cracking efficiency of a straight tubular reactor and a coil reactor. The procedure is the same as Example 1 except that the residual heavy hydrocarbon material discharged from the coil reactor is recycled back to the feed. Recycle is not used with the straight tubular reactor. The results are shown in Table 5.

Table 5: Conversion efficiency of straight tubular reactor versus a coil reactor

Sample	Reactor Type	Coil Reactor Residence Time (s)	Temp (C)	Conversion* (%)	Reaction Rate Constant Ln(K)
NST	Nozzle and Straight Tubular Reactor	0.3	460	26	-0.13
NCR	Nozzle and Coil Reactor	0.3	445	21	-.07

* Conversion refers to the amount of heavy hydrocarbon material converted to distillates.

[0112] This example demonstrates the nozzle and coil reactor combination is more efficient than the nozzle and straight tubular reactor. The reaction rate constant of the nozzle/coil combination is twice that of the nozzle/straight tubular combination.

Example 3

[0113] The procedure for this example is the same as Example 1. One run was performed using only the nozzle reactor and another run used both the nozzle reactor and the coil reactor. The carbon profile for each run is shown in Table 6.

Table 6: Conversion of heavy hydrocarbon material

Carbon Profile	Feed (wt%)	Nozzle Reactor Only Profile (%)	Nozzle/Coil Reactor Profile (%)
C1-C50	51.4	57.3	68.3
C50-C100	17.3	18.8	17.6
C100+	31.3	23.8	14.1

* Conversion refers to the amount of heavy hydrocarbon material converted to distillates.

[0114] This example demonstrates that the combination of the nozzle and coil reactor converts over 50 wt% of the heaviest material (the C100+ material) into C50-C100. It is significantly better than the conversion achieved by the nozzle reactor alone. It should be noted that C42+ material has a boiling point of 525 °C or higher.

[0115] In view of the many possible embodiments to which the principles of the disclosed invention may be applied, it should be recognized that the illustrated embodiments are only preferred examples of the invention and should not be taken as limiting the scope of the invention. Rather, the scope of the invention is defined by the following claims. We therefore claim as our invention all that comes within the scope and spirit of these claims.

[0116] The terms recited in the claims should be given their ordinary and customary meaning as determined by reference to relevant entries (e.g., definition of “plane” as a carpenter’s tool would not be relevant to the use of the term “plane” when used to refer to an airplane, etc.) in dictionaries (e.g., widely used general reference dictionaries and/or relevant technical dictionaries), commonly understood meanings by those in the art, etc., with the understanding that the broadest meaning imparted by any one or combination of these sources should be given to the claim terms (e.g., two or more relevant dictionary entries should be combined to provide the broadest meaning of the combination of entries, etc.) subject only to the following exceptions: (a) if a term is used herein in a manner more expansive than its ordinary and

customary meaning, the term should be given its ordinary and customary meaning plus the additional expansive meaning, or (b) if a term has been explicitly defined to have a different meaning by reciting the term followed by the phrase "as used herein shall mean" or similar language (e.g., "herein this term means," "as defined herein," "for the purposes of this disclosure [the term] shall mean," etc.). References to specific examples, use of "i.e.," use of the word "invention," etc., are not meant to invoke exception (b) or otherwise restrict the scope of the recited claim terms. Other than situations where exception (b) applies, nothing contained herein should be considered a disclaimer or disavowal of claim scope. The subject matter recited in the claims is not coextensive with and should not be interpreted to be coextensive with any particular embodiment, feature, or combination of features shown herein. This is true even if only a single embodiment of the particular feature or combination of features is illustrated and described herein. Thus, the appended claims should be read to be given their broadest interpretation in view of the prior art and the ordinary meaning of the claim terms.

[0117] As used herein, spatial or directional terms, such as "left," "right," "front," "back," and the like, relate to the subject matter as it is shown in the drawing FIGS. However, it is to be understood that the subject matter described herein may assume various alternative orientations and, accordingly, such terms are not to be considered as limiting. Furthermore, as used herein (i.e., in the claims and the specification), articles such as "the," "a," and "an" can connote the singular or plural. Also, as used herein, the word "or" when used without a preceding "either" (or other similar language indicating that "or" is unequivocally meant to be exclusive -- e.g., only one of x or y, etc.) shall be interpreted to be inclusive (e.g., "x or y" means one or both x or y). Likewise, as used herein, the term "and/or" shall also be interpreted to be inclusive (e.g., "x and/or y" means one or both x or y). In situations where "and/or" or "or" are used as a conjunction for a group of three or more items, the group should be interpreted to include one item alone, all of the items together, or any combination or number of the items. Moreover, terms used in the specification and claims such as have, having, include, and including should be construed to be synonymous with the terms comprise and comprising.

[0118] Unless otherwise indicated, all numbers or expressions, such as those expressing dimensions, physical characteristics, etc. used in the specification (other than the claims) are understood as modified in all instances by the term “approximately.” At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the claims, each numerical parameter recited in the specification or claims which is modified by the term “approximately” should at least be construed in light of the number of recited significant digits and by applying ordinary rounding techniques. Moreover, all ranges disclosed herein are to be understood to encompass and provide support for claims that recite any and all subranges or any and all individual values subsumed therein. For example, a stated range of 1 to 10 should be considered to include and provide support for claims that recite any and all subranges or individual values that are between and/or inclusive of the minimum value of 1 and the maximum value of 10; that is, all subranges beginning with a minimum value of 1 or more and ending with a maximum value of 10 or less (e.g., 5.5 to 10, 2.34 to 3.56, and so forth) or any values from 1 to 10 (e.g., 3, 5.8, 9.9994, and so forth).

WHAT IS CLAIMED IS:

1. A reactor comprising:
a tube including an internal passage; and
a fluid located in the internal passage of the tube, the fluid including heavy hydrocarbon material;
wherein the internal passage of the tube includes alternating linear sections and curved sections; and
wherein the reactor is oriented vertically and the fluid moves downward through the tube.
2. The reactor of claim 1 wherein some or all of the linear sections slope downward.
3. The reactor of claim 1 wherein each one of the linear sections is approximately 3 ft to approximately 10 ft long.
4. The reactor of claim 1 wherein the internal passage includes at least three, four, or five alternating linear sections and curved sections.
5. The reactor of claim 1 wherein the internal passage lies substantially on a plane.
6. The reactor of claim 1 wherein each one of the curved sections curve less than 180°.
7. The reactor of claim 1 wherein the internal passage is at least approximately 6 inches wide.
8. The reactor of claim 1 wherein the reactor is at least approximately 10 feet high.
9. The reactor of claim 1 wherein the fluid includes a cracking fluid.
10. The reactor of claim 1 wherein a portion of the heavy hydrocarbon material is converted into distillates in the reactor.
11. The reactor of claim 1 wherein the temperature of the heavy hydrocarbon material in the reactor is approximately 410 °C to approximately 490 °C.

12. A reactor system comprising:

a nozzle reactor including a first entry opening leading to a first input passage, a second entry opening, and an exit opening, wherein the first entry opening, the second entry opening, and the exit opening are in fluid communication with each other, and wherein the first input passage includes a convergent section followed by a divergent section; and

a tubular reactor in fluid communication with the exit opening of the nozzle reactor, the tubular reactor including an internal passage having alternating linear sections and curved sections.

13. The reactor system of claim 21 wherein the internal passage in the tubular reactor has a substantially planar orientation.

14. The reactor system of claim 12 wherein the tubular reactor is oriented vertically and fluid received from the nozzle reactor moves downward through the tubular reactor.

15. The reactor system of claim 12 wherein the internal passage in the tubular reactor is at least approximately 6 inches wide.

16. The reactor system of claim 12 comprising a fluid moving through the first input passage, wherein the fluid reaches at least Mach 1 as it moves through the first input passage.

17. The reactor system of claim 12 comprising an effluent material that exits the nozzle reactor and enters the tubular reactor, wherein the effluent material has a residence time in the tubular reactor of approximately 0.05 s to 1.5 s.

18. The reactor system of claim 12 comprising an effluent material that exits the nozzle reactor and enters the tubular reactor, wherein the effluent material has a linear velocity in the tubular reactor of approximately 4 m/s to 40 m/s.

19. The reactor system of claim 12 comprising:

a cracking fluid that enters the nozzle reactor through the first entry opening; and

a feed including heavy hydrocarbon material, the feed entering the nozzle reactor through the second entry opening.

20. A method comprising:

reacting heavy hydrocarbon material in a reactor and converting a portion of the heavy hydrocarbon material into distillates;

wherein the reactor includes a tube having an internal passage;

wherein the reactor is oriented vertically and the heavy hydrocarbon material moves downward through the tube; and

wherein the internal passage includes alternating linear sections and curved sections.

21. The method of claim 20 comprising reacting the heavy hydrocarbon material with a cracking fluid such as steam or natural gas.

22. The method of claim 20 wherein the heavy hydrocarbon material has a residence time in the reactor of approximately 0.05 s to 1.5 s.

23. The reactor of claim 20 wherein the heavy hydrocarbon material has a linear velocity in the reactor of approximately 4 m/s to 40 m/s.

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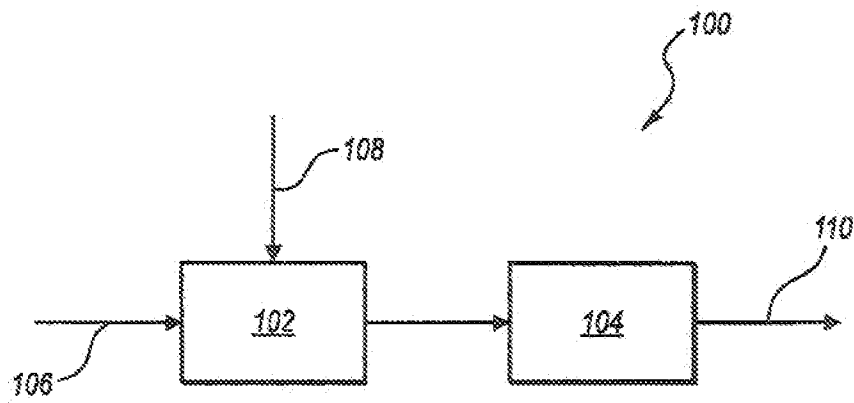


FIG. 1

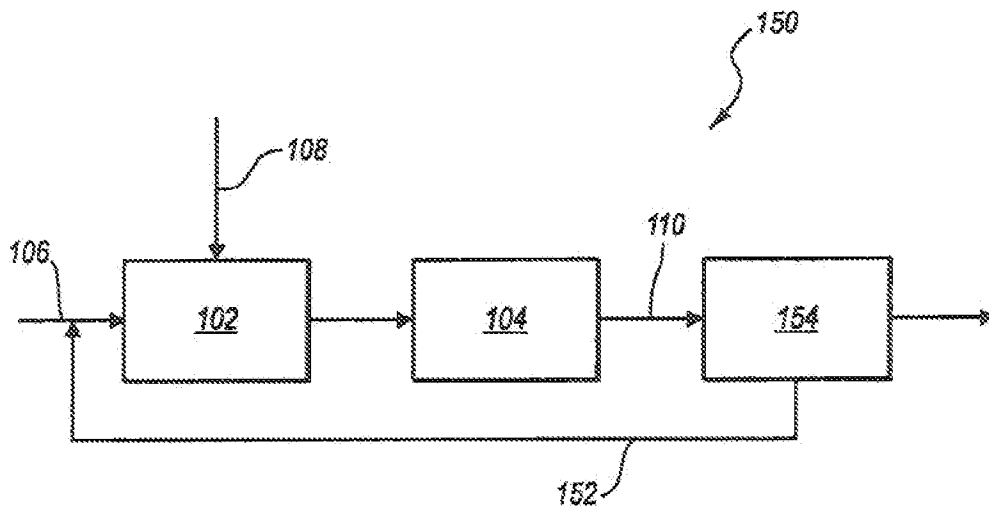


FIG. 2

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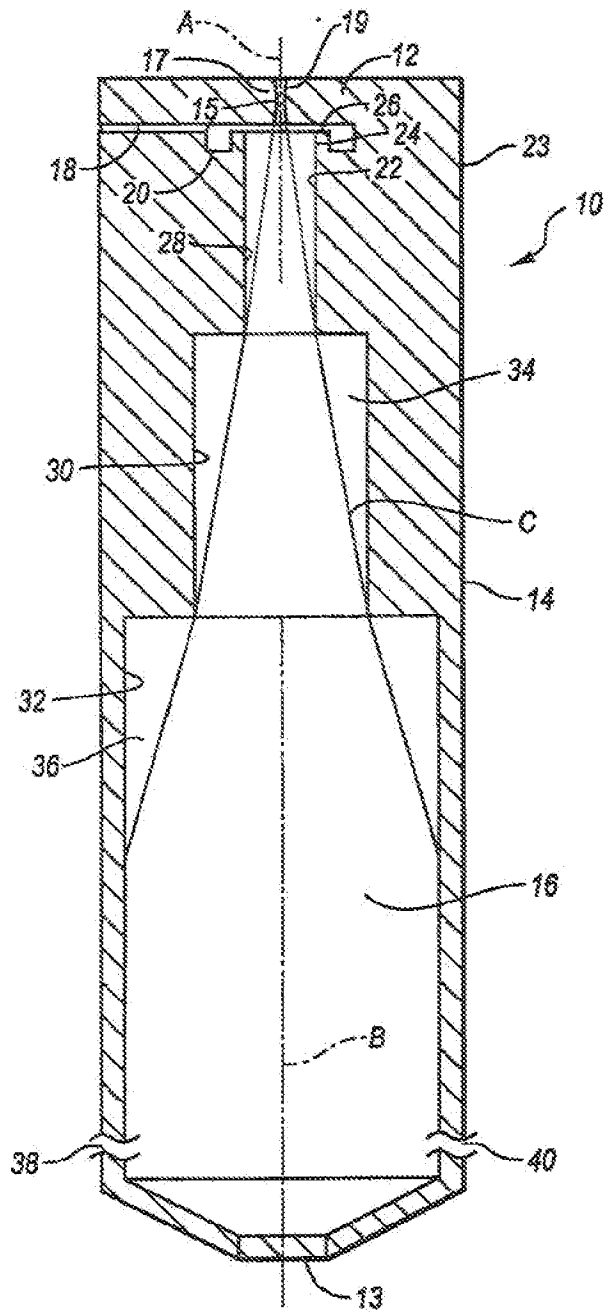


FIG. 3

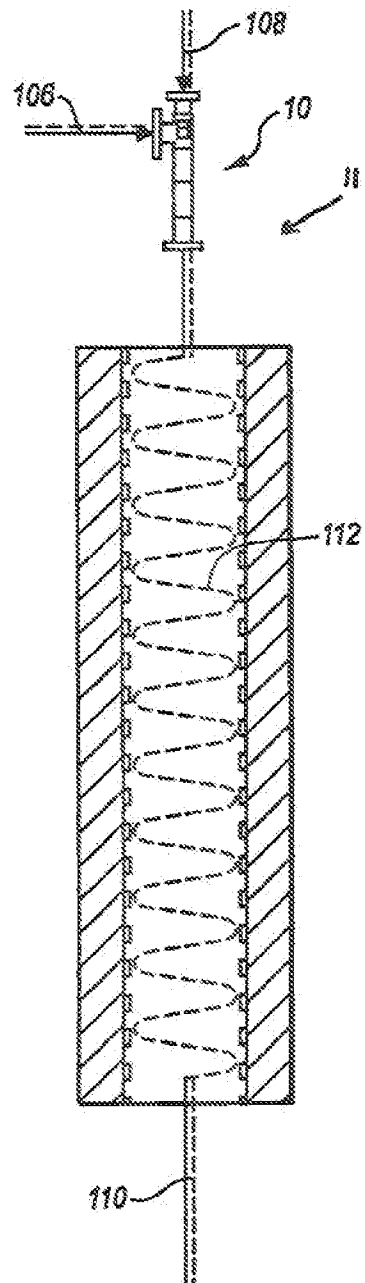


FIG. 4

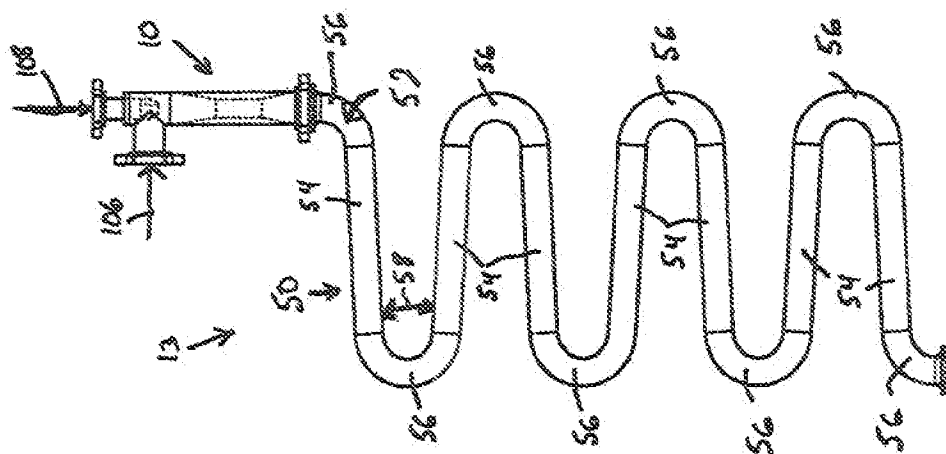


FIG. 5

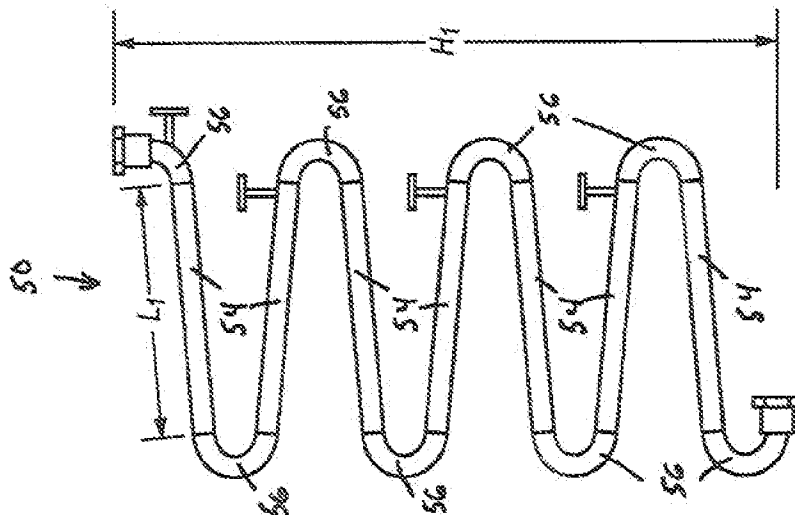


FIG. 6

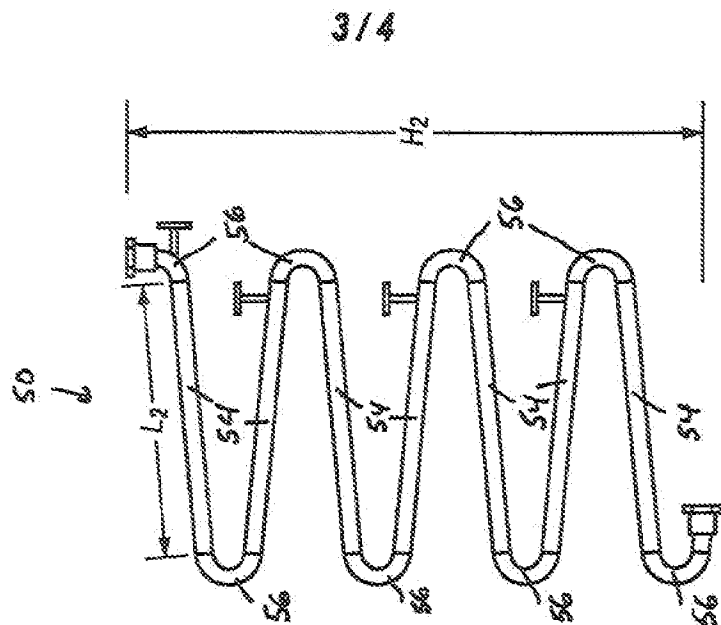


FIG. 7

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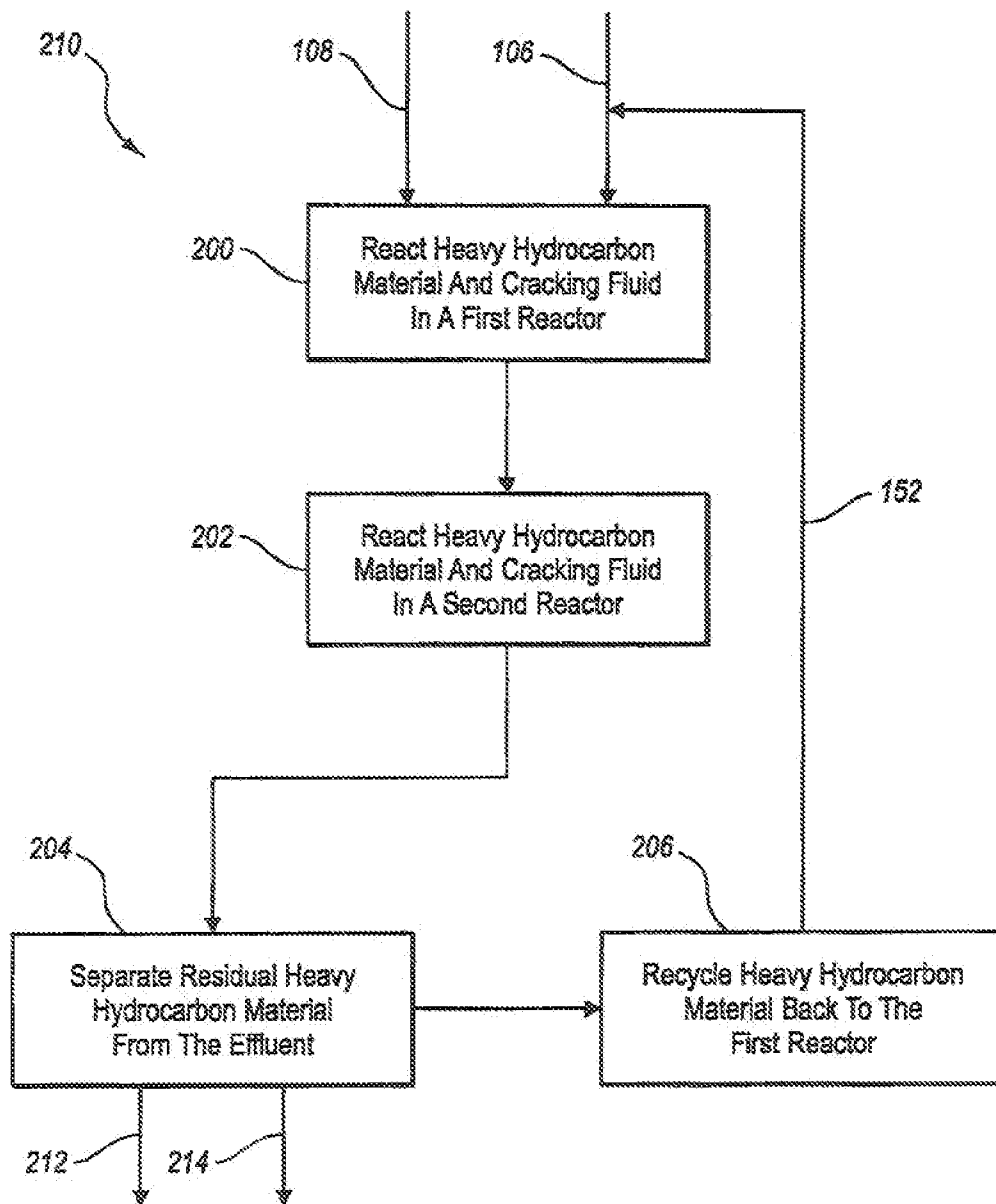


FIG. 8