

BACKGROUND OF THE INVENTION

[0003] Cryogenic liquefaction of natural gas to form liquefied natural gas (often referred to as “LNG”) is often used to more economically transport natural gas over large distances. However, this LNG process is generally expensive, and there are limited regasification facilities in only a few countries for handling the LNG. Converting natural gas to higher molecular weight hydrocarbons which, due to their higher density and value, are able to be more economically transported as a liquid can significantly expand the market for natural gas, particularly stranded natural gas produced far from

populated regions. While a number of processes for the conversion of natural gas to higher molecular weight hydrocarbons have been developed, these processes have not gained widespread industry acceptance due to their limited commercial viability. Typically, these processes suffer from high capital and operating costs and/or relatively low carbon efficiencies that have limited their use.

BRIEF SUMMARY OF THE INVENTION

[0004] To achieve the foregoing and other objects, and in accordance with the purposes of the present invention, as embodied and broadly described herein, one embodiment of the present invention is a process comprising reacting at least alkyl bromides over a catalyst in at least one conversion reactor to produce at least an effluent stream comprising higher molecular weight hydrocarbons and hydrogen bromide. The process may further comprise removing a portion of the catalyst from the conversion reactor. The process may further comprise contacting the portion of the catalyst with a stripping gas to displace hydrocarbons from the portion of the catalyst. The process may further comprise contacting the portion of the catalyst with a first inert gas. The process may further comprise contacting the portion the catalyst with oxygen to form a regenerated catalyst by removal of coke. The process may further comprise contacting the regenerated catalyst with a second inert gas. The process may further comprise introducing at least a portion of the regenerated catalyst into the conversion reactor.

[0005] Another embodiment of the present invention is a process comprising reacting at least bromomethane over a crystalline alumino-silicate catalyst in at least one conversion reactor to produce at least an effluent stream comprising higher molecular weight hydrocarbons and hydrogen bromide. The process may further comprise introducing a portion of the catalyst from the conversion reactor into a two-stage stripping unit. The process may further comprise introducing a stripping gas into an upper stage of the two-stage stripping unit to displace hydrocarbons from the portion of the catalyst, the hydrocarbons comprising hydrocarbons having six or more carbon atoms. The process may further comprise introducing a first inert gas into a lower stage of the two-stage stripping unit to remove a quantity of the stripping gas from the portion

of the catalyst. The process may further comprise introducing the portion of the catalyst from the two-stage stripping unit into a regeneration reactor to form a regenerated catalyst, wherein the portion of the catalyst is contacted with an oxygen-containing stream for coke removal. The process may further comprise introducing at least a
5 portion of the regenerated catalyst into the conversion reactor.

[0006] Yet another embodiment of the present invention comprises a reactor system comprising a conversion reactor configured for reaction of at least alkyl bromides over a catalyst to produce at least a stream comprising higher molecular weight hydrocarbons and hydrogen bromide. The reactor system may comprise a two-
10 stage stripping unit configured to receive a portion of the catalyst from the conversion reactor. The two-stage stripping unit may comprise a first stripping stage configured for contact of the portion of the catalyst with a stripping gas, and a second stripping stage configured for contact of the portion of the catalyst with an inert gas. The reactor system may further comprise a regeneration reactor configured for oxidation of the
15 portion of the catalyst from the two-stage stripping unit, and a second stripping unit configured for contact of the portion of the catalyst from the regeneration reactor with an inert gas.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The accompanying drawings, which are incorporated in and form a part of
20 the specification, illustrate the embodiments of the present invention and, together with the description, serve to explain the principles of the invention.

[0008] In the drawings:

[0009] FIG. 1 is a schematic diagram of one embodiment of a reactor-regenerator system of the present invention;

25 [0010] FIG. 2 is a schematic diagram of another embodiment of a reactor-regenerator system of the present invention;

[0011] FIG. 3 is a schematic diagram of yet another embodiment of a reactor-regenerator system of the present invention;

[0012] FIG. 4 is a schematic diagram of one embodiment for cooling a conversion
30 reactor of the present invention;

[0013] FIG. 5 is a schematic diagram of another embodiment for cooling a conversion reactor of the present invention; and

[0014] FIG. 6 is a schematic diagram of one embodiment of a process for producing higher molecular weight hydrocarbons.

5 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0015] Embodiments of the present invention disclose processes and systems that include the conversion of alkyl bromides to higher molecular weight hydrocarbons in circulating reactor-regenerator systems. In particular embodiments, the circulating reactor-regenerator systems utilize continuous or intermittent circulation of a solid catalyst between a conversion reactor and a regeneration process that includes a two-stage stripping unit.

[0016] There may be many potential advantages to the processes and systems of the present invention, only some of which are alluded to herein. One of the many potential advantages of embodiments of the processes and systems of the present invention is that use of the circulating catalyst reactor-regenerator systems in which the catalyst is continuously or intermittently regenerated should allow continuous reactor operation because regenerated catalyst is added to the conversion reactor as coke accumulates on the catalyst in the conversion reactor with deactivated catalyst withdrawn. Moreover, addition of the regenerated catalyst to the conversion reactor should minimize the amount of catalyst and reactor volume needed for a given amount of production. Even further, the two-stage stripping unit should allow for recovery of hydrocarbons from the catalyst prior to oxidative regeneration, thus minimizing carbon loss from the catalyst. In particular, at least a portion of the coke formed on the catalyst during alkyl bromide conversion may be in the form of C₆+ hydrocarbons (e.g., aromatic compounds) which are produced, for example, within the crystalline cages of the catalyst, and which can be stripped from the catalyst and recovered prior to regeneration, in accordance with embodiments of the present invention.

[0017] The term "higher molecular weight hydrocarbons" as used herein refers to hydrocarbons comprising a greater number of carbon atoms than one or more components of the feedstock. For example, natural gas is typically a mixture of light

hydrocarbons, predominately methane, with lesser amounts of ethane, propane, and butane, and even smaller amounts of longer chain hydrocarbons such as pentane, hexane, etc. When natural gas is used as a feedstock, higher molecular weight hydrocarbons produced in accordance with embodiments of the present invention may include a hydrocarbon comprising C₂ and longer hydrocarbon chains, such as ethane, ethylene, propane, propylene, butane, butylenes, C₅+ hydrocarbons, aromatic hydrocarbons, and mixtures thereof. In some embodiments, part or all of the higher molecular weight hydrocarbons may be used directly as a product (e.g., LPG, motor fuel, etc.). In other instances, part or all of the higher molecular weight hydrocarbons may be used as an intermediate product or as a feedstock for further processing. In yet other instances, part or all of the higher molecular weight hydrocarbons may be further processed, for example, to produce gasoline grade fuels, diesel grade fuels, and fuel components. In some embodiments, part or all of the higher molecular weight hydrocarbons obtained by the processes of the present invention can be used directly as a motor gasoline fuel having a substantial aromatic content, as a fuel blending stock, or as feedstock for further processing such as an aromatic feed to a process producing aromatic polymers such as polystyrene or related polymers.

[0018] The term "olefins," as used herein refers to hydrocarbons that contain two to six carbon atoms and at least one carbon-carbon double bond. In some embodiments, with some zeolite catalysts, olefins are produced in the reactor-regenerator systems discussed below along with other higher molecular weight hydrocarbons, such as ethane and propane, for example. The olefins may be further processed if desired. For instance, in some instances, the olefins produced by the processes of the present invention may be further reacted in a polymerization reaction (e.g., a reaction using a metallocene catalyst) to produce poly(olefins), which may be useful in many end products such as plastics or synthetic lubricants. In other embodiments, the olefins may be recycled back to the bromination stage, for example. It should be noted that the olefins (e.g., C₂ and C₃ olefins) are substantially more reactive than the respective alkane (ethane and propane) and are observed to be almost completely converted to di-bromoethylene and di-bromopropylene.

Nevertheless, di-bromoethylene and di-bromopropylene can be efficiently converted to higher molecular weight hydrocarbons over zeolite catalysts.

[0019] The end use of the higher molecular weight hydrocarbons may depend on the particular catalyst employed for the coupling reaction carried out in the reactor-regenerator systems discussed below, as well as the operating parameters employed in the process. Other uses will be evident to those skilled in the art with the benefit of this disclosure.

[0020] The term "alkyl bromides," as used herein, refers to mono-, di-, and tri-brominated alkanes, and combinations of these. Poly-brominated alkanes include di-brominated alkanes, tri-brominated alkanes and mixtures thereof. These alkyl bromides may be reacted over suitable catalysts so as to form higher molecular weight hydrocarbons.

[0021] The term "lower molecular weight alkanes," as used herein, refers to methane, ethane, propane, butane, pentane or mixtures of two or more of these individual alkanes. Lower molecular weight alkanes may be used as a feedstock for the methods described herein. For example, the lower molecular weight alkanes may be reacted with bromine to produce alkyl bromides. The lower molecular weight alkanes may be from any suitable source, for example, any source of gas that provides lower molecular weight alkanes, whether naturally occurring or synthetically produced. Examples of sources of lower molecular weight alkanes for use in the processes of the present invention include, but are not limited to, natural gas, coal-bed methane, regasified liquefied natural gas, gas derived from gas hydrates and/or clathrates, gas derived from anaerobic decomposition of organic matter or biomass, gas derived in the processing of tar sands, and synthetically produced natural gas or alkanes. Combinations of these may be suitable as well in some embodiments. In some embodiments, it may be desirable to treat the feed gas to remove undesirable compounds, such as sulfur compounds and carbon dioxide.

[0022] Suitable sources of bromine that may be used in various embodiments of the present invention include, but are not limited to, elemental bromine, bromine salts, aqueous hydrobromic acid, metal bromide salts, and the like. Combinations may be

suitable, but as recognized by those skilled in the art, using multiple sources may present additional complications.

[0023] Certain embodiments of the methods of the invention are described below. Although major aspects of what is to be believed to be the primary chemical reactions involved in the methods are discussed in detail as it is believed that they occur, it should be understood that side reactions may take place. One should not assume that the failure to discuss any particular side reaction herein means that the side reaction does not occur. Conversely, those that are discussed should not be considered exhaustive or limiting. Additionally, although figures are provided that schematically show certain aspects of the methods of the present invention, these figures should not be viewed as limiting on any particular method of the invention.

[0024] FIG. 1 is a schematic diagram illustrating a reactor-regenerator system in accordance with embodiments of the present invention. In the illustrated embodiment, the reactor-regenerator system 5 includes the following: a conversion reactor 10 for converting alkyl bromides to higher molecular weight hydrocarbons; a two-stage stripping unit 15 for receiving deactivated catalyst from the conversion reactor 10 and recovering hydrocarbons there from; a regeneration reactor 20 for receiving the stripped, deactivated catalyst from the two-stage stripping unit 15 and removing coke deposits there from by oxidative regeneration; and a second stripping unit 25 for receiving the regenerated catalyst from the regeneration reactor 20 and removing residual oxygen and other components there from. As previously mentioned, employment of the two-stage stripping unit 15 may allow for recovery of hydrocarbons from the catalyst prior to regeneration, which can minimize carbon loss while maximizing process efficiency, in accordance with embodiments of the present invention.

[0025] As illustrated, a feed stream 30 may be introduced to the conversion reactor 10. The feed stream 30 introduced to the conversion reactor 10 may comprise, for example, alkyl bromides, lower molecular weight alkanes (e.g., methane, ethane, etc.), and hydrogen bromide (HBr). The lower molecular weight hydrocarbons generally may be unreacted, excess alkanes that were not fully converted to alkyl bromides in a prior bromination stage, as should be appreciated by those of ordinary skill in the art,

with the benefit of this disclosure. The HBr generally may be a byproduct from the bromination of the lower molecular weight alkanes to alkyl bromides, as should also be appreciated by those of ordinary skill in the art, with the benefit of this disclosure. The alkyl bromides present in the feed stream 30 generally may include mono-brominated alkanes (e.g., mono-bromomethane, mono-bromoethane, mono-bromopropane, and the like) and poly-brominated alkanes (e.g., di-bromomethane, di-bromoethane, tri-bromoethane, and the like). In some embodiments, the ratio of mono-brominated alkanes to mono-brominated alkanes plus di-bromomethane ($RBr/(RBr + DBM)$) may be from about 0.6 to about 1.0. In one particular embodiment, this ratio may be from about 0.67 to about 0.9. In some embodiments, it may be desired to limit or otherwise restrict the concentration of di-bromomethane in the feed stream 30 such that the $RBr/(RBr + DBM)$ ratio is equal to or greater than about 0.9. In some embodiments, a separation unit may be used to reduce the concentration of di-bromomethane in the feed stream 30. Those of ordinary skill in the art, with the benefit of this disclosure, will appreciate that di-bromomethane generally has a higher selectivity to coke formation and, thus, reducing its concentration in the feed stream 30 may reduce the rate of coke formation in the conversion reactor 10 in accordance with embodiments of the present invention.

[0026] In the conversion reactor 10, the alkyl bromides in the feed stream 30 may be reacted over a suitable catalyst in the presence of HBr to produce higher molecular weight hydrocarbons and additional HBr. A conversion reactor effluent stream 35, which comprises higher molecular weight hydrocarbons and HBr, may be withdrawn from the conversion reactor 10. The conversion reactor effluent stream 35 may further comprise at least a portion of the excess, unreacted alkanes from the feed stream 30.

[0027] In the illustrated embodiment, the conversion reactor 10 further contains heat transfer coils 40 for cooling the conversion reactor 10. Where used, the heat transfer coils 40 generally can recover the heat of reaction from the dehydrohalogenation reactions in the conversion reactor 10, for example, so that catalyst can be maintained in a desirable temperature range. The conversion reactor 10 can be maintained, for example, at a temperature of less than about 500°C. In some embodiments, the conversion reactor 10 can be maintained at a temperature in the range of about 325°C to about 450°C and, alternatively, about 375°C to about 400°C.

While heat transfer coils 40 are illustrated, it should be understood that other mechanisms for cooling the conversion reactor 10 can be used in accordance with embodiments of the present invention, such as those depicted in the embodiment shown on FIG. 5 in which a portion of conversion reactor effluent stream 35 is cooled and recycled to the conversion reactor 10. It should be understood that use of a cooling mechanism, such as heat transfer coils 40, is optional and is not employed in some embodiments, for example, in which the temperature increase within the conversion reactor 10 resulting from the heat of reaction is within an acceptable range to minimize coke selectivity and maximize conversion rate such as between about 340° to about 420° C in the case of a ZSM-5 zeolite catalyst.

[0028] The catalyst used in the conversion reactor 10 may be any of a variety of suitable materials for catalyzing the conversion of the alkyl bromides to higher molecular weight hydrocarbons. In the illustrated embodiment, the conversion reactor 10 may comprise a fluidized bed 12 of the catalyst. The fluidized bed 12 of the catalyst may have certain advantages, such as constant removal of coke and a steady selectivity to product composition. In some embodiments, the catalyst may be a granular catalyst having a mean particle size in the range of about 30 microns to about 300 microns. Examples of suitable catalysts include a fairly wide range of materials that have the common functionality of being acidic ion-exchangers and which also contain a synthetic crystalline alumino-silicate oxide framework. The crystalline alumino-silicate may include a microporous or mesoporous crystalline aluminosilicate, but, in certain embodiments, may include a synthetic microporous crystalline zeolite, and, for example, being of the MFI structure such as ZSM-5. Further, the zeolites may be subjected to a chemical and/or hydrothermal de-alumination treatment, which has been found to substantially improve the tolerance of the catalyst to di-bromomethane and reduce the selectivity to coke. In certain embodiments, a portion of the aluminum in the crystalline alumino-silicate oxide framework may be substituted with magnesium, boron, gallium and/or titanium. In certain embodiments, a portion of the silicon in the crystalline alumino-silicate oxide framework may be optionally substituted with phosphorus. The crystalline alumino-silicate catalyst generally may have a significant anionic charge within the crystalline alumino-silicate oxide framework structure which may be balanced,

for example, by cations of elements selected from the group H, Li, Na, K or Cs or the group Mg, Ca, Sr or Ba or the group La or Ce. Although zeolitic catalysts may be commonly obtained in a sodium form, a protonic or hydrogen form (via ion-exchange with ammonium hydroxide, and subsequent calcining) is preferred, or a mixed
5 protonic/sodium form may also be used. The zeolite may also be modified by ion exchange with other alkali metal cations, such as Li, K, or Cs, with alkali-earth metal cations, such as Mg, Ca, Sr, or Ba, or with transition metal cations, such as Fe, Ni, Cu, Mn, Pb, V, W or with rare-earth metal cations La or Ce. Such subsequent ion-exchange, may replace the charge-balancing counter-ions, but furthermore may also
10 partially replace ions in the oxide framework resulting in a modification of the crystalline make-up and structure of the oxide framework. Moreover, the crystalline aluminosilicate or substituted crystalline aluminosilicate, in certain embodiments, may be subsequently impregnated with an aqueous solution of a Mg, Ca, Sr, Ba, La or Ce salt. In certain embodiments, the salts may be a halide salt, such as a bromide salt, such as
15 $MgBr_2$, $CeBr_3$ or other solid compound having Lewis acid functionality which has been found to reduce the deactivation rate of the base crystalline aluminosilicate or substituted aluminosilicate catalyst. Optionally, the crystalline aluminosilicate or substituted crystalline aluminosilicate may also contain between about 0.1 weight % to about 1 weight % Pt or about 0.1 weight % to about 5 weight % Pd. Although, such
20 materials are primarily initially crystalline, it should be noted that some crystalline catalysts may undergo some loss of crystallinity either due to initial ion-exchange or impregnation or due to operation at the reaction conditions or during regeneration and hence may also contain significant amorphous character, yet still retain significant, and in some cases improved activity.

25 [0029] Those of ordinary skill in the art should appreciate, with the benefit of this disclosure, that the particular higher molecular weight hydrocarbons produced will be dependent, for example, upon the catalyst employed in the conversion reactor 10, the composition of the alkyl bromides introduced into the conversion reactor 10, and the exact operating parameters employed in the conversion reactor 10. The particular
30 catalyst used in conversion reactor 10 will depend, for example, upon the particular higher molecular weight hydrocarbons that are desired. For example, when higher

molecular weight hydrocarbons having primarily C₃, C₄ and C₅+ gasoline-range aromatic compounds and heavier hydrocarbon fractions are desired, a ZSM-5 zeolite catalyst or modified ZSM-5 zeolite catalyst, such as a partially de-aluminated, ion-exchanged ZSM-5 catalyst, may be used. When it is desired to produce higher
5 molecular weight hydrocarbons comprising a mixture of olefins and C₅+ products, an X-type or Y-type zeolite catalyst or SAPO zeolite catalyst may be used. An example of a suitable zeolite includes an X-type, such as 10-X, although other zeolites with differing pore sizes and acidities, may be used in embodiments of the present invention.

[0030] Those of ordinary skill in the art, with the benefit of this disclosure, should
10 recognize that the catalyst in the conversion reactor 10 will generally undergo a loss of catalytic activity during use. The catalyst is generally considered significantly deactivated when it has accumulated an amount of coke in the range of about 10 to 20 weight % coke (as carbon) or greater. In accordance with present embodiments, the time required for deactivation of the catalyst can vary from a few hours to several days.
15 In some embodiments, the time required for deactivation can vary from about 6 hours to about 48 hours. Some of the factors, which most significantly impact the deactivation rate of the catalyst, include without limitation the composition of the feed (particularly the amount of di-bromomethane present), space velocity, temperature, and type of catalyst.

[0031] In general, the catalyst in the conversion reactor 10 becomes deactivated
20 due to the accumulation of "coke," which is generally a carbonaceous material generated on the catalyst during the alkyl bromide conversion. Some of the coke accumulated on the catalyst may be in form of desirable hydrocarbons, such one- and two-ring aromatic compounds, which may be lost if not recovered from the catalyst during catalyst regeneration. In addition, it is believed that some "hydrocarbon pool"
25 intermediates, which are formed in the crystalline cages of the catalyst may be lost if not recovered prior to regeneration. "Hydrocarbon pool" intermediates are believed to be substituted aromatics which undergo addition and are also cleaved into smaller fragments to yield C₃+ products.

[0032] To restore activity, the catalyst can be regenerated in accordance with
30 present embodiments. For regeneration of the deactivated catalyst, a stream 45 comprising at least a portion of deactivated catalyst (e.g., the catalyst with accumulated

coke) may be removed from the conversion reactor 10 and introduced into the two-stage stripping unit 15 that comprises an upper stripping stage 50 and a lower stripping stage 55. In an embodiment, the stream 45 can be continuously removed from the conversion reactor 10. In an alternative embodiment, the stream 45 can be
5 intermittently removed from the conversion reactor 10. As illustrated, the stream 45 may be withdrawn, for example, from an upper section of the conversion reactor 10. Alternatively, the stream 45 may be withdrawn from a lower section of the conversion reactor 10, as best seen in FIG. 2. While FIG. 1 illustrates the two-stage stripping unit 15 having only a single vessel, the two-stage stripping unit 15 may include one or more
10 vessels as will be appreciated by those of ordinary skill in the art, with the benefit of this disclosure. For example, the upper and lower stripping stages 50, 55 may be separate vessels in some embodiments.

[0033] In the upper stripping stage 50, the deactivated catalyst may be contacted with a stripping gas transported to the two-stage stripping unit 15 via stream 60. The
15 stripping gas generally should remove at least a portion of the C6+ hydrocarbons that may be on the deactivated catalyst. In one embodiment, the stripping gas may comprise a lower molecular weight alkane, such as methane, ethane, propane, or a combination thereof. Alternatively, the stripping gas may comprise a reducing gas, for example, such as hydrogen or a mixture containing hydrogen. It is believed that the
20 reducing gas may have the added beneficial effect of partially saturating the aromatic compounds or hydrocarbon pool intermediates residing in the micro-pores of the deactivated catalyst.

[0034] In the lower stripping stage 55, the deactivated catalyst may be contacted with a stream 65 comprising an inert gas, such as nitrogen. The inert gas generally
25 should remove at least a portion of the stripping gas from the deactivated catalyst, minimizing its loss thereof to oxidation in the regeneration reactor 20. The residence time of the deactivated catalyst in the upper stripping stage 50 generally may be greater than the residence time of the deactivated catalyst in the lower stripping stage 55, for example, to give sufficient time to desorb a significant portion of the adsorbed stripping
30 gas. In some embodiments, the residence time in the upper stripping stage 50 may be

in the range of about 5 minutes to about 120 minutes while the residence time in the lower stripping stage 55 may be in the range of about 1 minute to about 15 minutes.

[0035] A stream 70 comprising the C6+ hydrocarbons removed from the deactivated catalyst may be withdrawn from the two-stage stripping unit 15 and combined with the conversion reactor effluent stream 35. In this manner, at least a portion of the C6+ hydrocarbons that were adsorbed onto the catalyst in the conversion reactor 10 may be recovered, thus minimizing carbon loss from the catalyst. The C6+ hydrocarbons may be in the form of, for example, multi-ring aromatic compounds and/or hydrocarbon pool intermediates. The stream 70 of the C6+ hydrocarbons may further comprise at least portion of the stripping and inert gases introduced into the two-stage stripping unit 15 via stream 60 and stream 65, respectively.

[0036] Another stream 75 comprising the stripped, deactivated catalyst may be withdrawn from the first stripping unit 15 and introduced into the regeneration reactor 20 for contact with oxygen to regenerate at least a portion of the catalyst. In some embodiments, the regeneration reactor 20 may contain a fluidized bed 22 of the catalyst. An oxygen-containing gas stream 80 may be fed to the regeneration reactor 20. In the illustrated embodiment, the oxygen-containing gas stream 80 is fed at or near the bottom of the regeneration reactor 20. The oxygen-containing gas stream 80 may include oxygen and/or air, for example. In the regeneration reactor 20, oxygen from stream 80 reacts with the coke deposits on the deactivated catalyst to yield carbon oxides (e.g., CO, CO₂) and steam, thus removing at least a portion of the coke deposits on the deactivated catalyst by oxidation. In this manner, the deactivated catalyst can be regenerated for reuse in the conversion reactor 10. Surprisingly, it has been discovered that embodiments of the catalyst can still be active with up to about 20 weight % coke on the catalyst. Accordingly, in some embodiments, the catalyst can be regenerated in the regeneration reactor 20 to yield a regenerated catalyst having less than about 1 weight % to about 10 weight % coke on the catalyst. In some embodiments, the catalyst can be fully regenerated, which ensures the highest level of catalyst activity. As used herein, a catalyst is considered fully regenerated if the amount of coke on the catalyst is less than about 0.1 weight %. However, it has been discovered that the coke formation rate in the conversion reactor 10 may be reduced if some coke is left on the

catalyst as the most active coke-forming sites on the catalyst are also the most easily deactivated leading to a partial self-passivating effect. Accordingly, it may be desirable to leave some coke on the catalyst in accordance with embodiments of the present invention. For example, the catalyst can be regenerated in the regeneration reactor 20 to yield a regenerated catalyst having about 2 weight % to about 10 weight % coke on the catalyst and, alternatively, from about 2 weight % to about 5 weight % coke on the catalyst.

[0037] The regeneration reactor 20 generally may operate at a temperature in the range of about 450°C to about 650°C and a pressure in the range of about 1 atmosphere to about 50 atmospheres. In accordance with embodiments of the present invention, it can be important to keep the temperature of the catalyst below about 650°C and more preferably to keep the catalyst in the range of about 500° to about 550°C. In some embodiments, this may be achieved by dilution of the oxygen or air with nitrogen (such as by recycling a portion of the regeneration off gas). In some embodiments, the regeneration reactor 20 may include heat transfer coils 85 for recovering heat from the exothermic, oxidative reactions occurring in the regeneration reactor 20. The regeneration reactor 20 may be maintained, for example, at a temperature of less than about 650°C and, alternatively, below about 550°C. As illustrated, the heat transfer coils 85 may be disposed in the fluidized bed 22 of the catalyst. Maintenance of temperature below these levels may be desirable, in accordance with embodiments of the present invention, to prevent high-temperature and/or hydrothermal degradation of the catalyst that could occur at higher temperatures in some embodiments. While heat transfer coils 85 are illustrated, it should be understood that other mechanisms for cooling the regeneration reactor 20 can be used in accordance with embodiments of the present invention.

[0038] A stream 90 comprising the regenerated catalyst may be withdrawn from the regeneration reactor 20 and introduced into the second stripping unit 25. In the second stripping unit 25, the regenerated catalyst may be contacted with an inert gas stream 95, which may be fed to the bottom of the second stripping unit 25 as seen in FIG. 1. The inert gas stream 95 may comprise an inert gas, such as nitrogen, among others. The inert gas generally should remove residual oxygen, carbon oxides, and/or

steam that may be retained on the regenerated catalyst. For example, the inert gas may displace residual oxygen, carbon oxides, and/or steam that may be retained in the interstitial spaces between catalyst granules or adsorbed on the catalyst. The inert gas used in second stripping unit 25 may be the same or different than the inert gas used in the lower stripping stage 55. In the illustrated embodiment, the second stripping unit 25 has a single stripping stage. A catalyst feed stream 100 comprising at least a portion of the regenerated catalyst may be withdrawn from the second stripping unit 25 and introduced into the conversion reactor 10. As illustrated, the catalyst feed stream 100 may introduce the regenerated catalyst into a lower section of the conversion reactor 10. Alternatively, the catalyst feed stream 100 may be introduced into an upper section of the conversion reactor 10, as best seen in FIG. 2.

[0039] The residual air or oxygen from the oxygen-containing gas stream 80 may be withdrawn from the regeneration reactor 20 via stream 105. Carbon oxides and/or steam generated in the regeneration reactor 20 by the oxidation of the coke on the deactivated catalyst may also be removed via stream 105. As illustrated, stream 105 may be combined with stream 110 from the second stripping unit 25. In present embodiments, the stream 110 may comprise the residual inert gas as well as oxygen, carbon oxides, and/or steam removed from the regenerated catalyst in the second stripping unit 25. As the combined streams from the regeneration reactor 20 and the second stripping unit 25 may contain small amounts of bromine-containing species, as well as excess unreacted oxygen, this combined stream may be directed to a unit for bromine recovery (e.g., HBr oxidation unit 265 on FIG. 6), wherein the bromine-containing species may be converted to elemental bromine and recovered for re-use.

[0040] Referring now to FIG. 2, a first moving-bed reactor system 115 for converting alkyl bromides in the feed stream 30 to higher molecular hydrocarbons is illustrated in accordance with embodiments of the present invention. The moving-bed reactor system 115 differs from the reactor-regenerator system 5 shown on FIG. 1, in that the illustrated embodiment includes a moving bed 14 of a pelletized catalyst, which may be of any suitable shape, such as spherical. In some embodiments, the pelletized catalyst may have a mean particle size in the range of about 1 millimeter to about 10 millimeters. Examples of suitable pelletized catalyst include the catalysts described

above with respect to FIG. 1. As illustrated, the regenerated catalyst may be introduced at or near the top of the conversion reactor 10 via catalyst feed stream 100. Those of ordinary skill will recognize that the introduction of the regenerated catalyst to the conversion reactor 10 may be intermittent or continuous as desired for a particular application. Within the conversion reactor 10, the catalyst moves downward, concurrently to the upward flow of vapor within the conversion reactor 10. The downward flow of the catalyst may be intermittent or continuous as will be recognized by those of ordinary skill with the benefit of this disclosure. A stream 45 comprising deactivated catalyst may be removed from at or near the bottom of the conversion reactor 10 and introduced into the two-stage stripping unit 15. The other process components depicted in FIG. 2, including the two-stage stripping unit 15, regeneration reactor 20, and second stripping unit 25, may be substantially similar in function and operation as the analogous components described above with respect to FIG. 1 with the exception of riser 120, which lifts the regenerated catalyst for introduction at or near the top of the conversion reactor 10. In the illustrated embodiment, the riser 120 receives a stream 125 comprising the regenerated catalyst from the second stripping unit 25 and uses a gas stream 130 to lift the regenerated catalyst so that catalyst feed stream 100 can be introduced at or near the top of the conversion reactor 10. The gas stream 130 may comprise an inert gas as will be apparent to those of ordinary skill in the art with the benefit of this disclosure. In an alternative embodiment (not shown), a mechanical conveying device may be used in the riser 120 for mechanically lifting the regenerated catalyst and conveying it to the conversion reactor 10.

[0041] FIG. 3 illustrates an alternative moving-bed reactor system 135 in accordance with alternative embodiments of the present invention. In the illustrated embodiment, the alternative moving-bed reactor system 135 is substantially similar in function and operation to the embodiment described above with respect to FIG. 2, except that the catalyst is arranged in an annular bed 140. In the illustrated embodiment, the reactants fed to the reactor in feed stream 30 pass radially through the downward flowing catalyst in the annular bed 140. While inward-to-outward reactant flow across the annular bed 140 is depicted in FIG. 3, it may be advantageous for reactants to flow outward to inward in alternative embodiments of the present invention.

[0042] FIG. 4 illustrates one technique for cooling the conversion reactor 10 in accordance with embodiments of the present invention. As illustrated, the conversion reactor 10 may contain heat transfer coils 40 disposed in a catalyst bed 145, which may be, for example, a fluidized- or moving-bed as previously discussed. A suitable heat transfer fluid, such as boiling water, may be passed through the heat transfer coils 40 for recovering the heat of reaction from the dehydrohalogenation reaction occurring in the conversion reactor 10.

[0043] FIG. 5 illustrates another technique for cooling the conversion reactor 10 in accordance with embodiments of the present invention. In the illustrated embodiment, a slipstream 150 of the conversion reactor effluent stream 35 is cooled in heat exchanger 155. In one particular embodiment, the slipstream 150 may contain lower molecular weight alkanes, such as methane, ethane, and/or propane. The cooled slipstream 160, which may have been partially condensed, can be sent to separator 165 for vapor-liquid phase separation. In the separator 165, the cooled slipstream 160 may be separated into a gas stream 170 and a liquid stream 175. The gas stream 170 may be fed to compressor 180 that compresses the gas stream 170 and delivers a compressed gas stream 185 to the conversion reactor 10. As illustrated, the compressed gas stream 185 may be combined with the feed stream 30 prior to introduction into the conversion reactor 10, thus cooling the alkyl bromides contained in the feed stream 30. In addition to cooling the conversion reactor 10, it has been found that the presence of alkanes, such as propane, may serve as hydrogen donors, thus potentially lowering the selectivity of the alkyl bromide conversion to coke.

[0044] In accordance with embodiments of the present invention, the reactor-regenerator systems described above with respect to FIGS. 1-5 for the conversion of alkyl bromides to higher molecular weight hydrocarbons may be used in a bromine-based process for the production of higher molecular weight hydrocarbons from lower molecular weight alkanes. For example, a stream of lower molecular weight hydrocarbons may be reacted with bromine from a suitable bromine source to produce alkyl bromides. These alkyl bromides may then be reacted over suitable catalyst so as to form higher molecular weight hydrocarbons. The above-described reactor-regenerator systems may be used for this alkyl bromides conversion.

[0045] A block flow diagram generally depicting an embodiment of a process 190 for producing higher molecular weight hydrocarbons from lower molecular weight alkanes is illustrated in FIG. 6. As illustrated by FIG. 6, the process 190 may include a bromination stage 195 in which a gas stream 200 comprised primarily of methane, for example, derived from a mixture of feed gas plus a recycled gas stream, may react with bromine from bromine stream 205 to produce alkyl bromides and HBr. In some embodiments, the bromine may be a substantially dry bromine vapor. In some embodiments, the bromination stage 195 may include separate and parallel bromination of methane and C₂+ alkanes contained in stream 310. In some embodiments, the bromination stage 195 further may include separate and parallel bromination of C₂ alkanes and C₃+ alkanes. A stream 210 comprising the resultant alkyl bromides may be withdrawn from the bromination stage 195 and fed into a circulating catalyst reactor-regenerator system 215. In the circulating catalyst reactor-regenerator system 215, the alkyl bromides may be reacted over a suitable catalyst in the presence of HBr to produce higher molecular weight hydrocarbons. In addition, as described above with respect to FIGS. 1-5, the catalyst in the circulating catalyst reactor-regenerator system 215 may be regenerated by a process that includes, for example, a two-stage stripping unit 15, a regeneration reactor 20, and a second stripping unit 25.

[0046] A reactor effluent stream 220 may be withdrawn from the reactor-regenerator system 215 and introduced to a hydrogen bromide ("HBr") removal and product recovery unit 225. In some embodiments, the reactor effluent stream 220 may comprise unreacted hydrocarbons (e.g., C₁-C₃ hydrocarbons), higher molecular weight hydrocarbons produced by the reaction of alkyl bromides over a suitable catalyst in reactor-regenerator system 215, and HBr. As illustrated, a feed gas stream 230 comprising lower molecular weight hydrocarbons, such as natural gas, can also be introduced to the product recovery unit 225.

[0047] In the HBr removal and product recovery unit 225, the HBr generated in the bromination stage 195 and the reactor-regenerator system 215 may be separated from the hydrocarbon components. As illustrated, separation of the HBr may be combined with separation of the hydrocarbon components into their respective fractions for product recovery and recycle. For example, the HBr removal and product recovery

unit 225 may separate the respective feeds into a methane stream 235, an ethane stream 240, an HBr stream 245, a propane stream 250, a butane stream 255, and a liquid product stream 260. Any suitable technique may be used for separation of the HBr and hydrocarbons in the HBr removal and product recovery unit 225, including, for example, cryogenic separation, fractionation, extractive distillation, or a refrigerated lean-oil process, among others, as should be evident to those of ordinary skill in the art with the benefit of this disclosure. In the illustrated embodiment, a portion of the methane stream 235 is recycled to bromination stage 195. The ethane stream 240, propane stream 250, and butane stream 255 may be combined into stream 310 and recycled to the bromination stage 195 as illustrated by FIG. 6, for example. While not illustrated, stream 240 and a mixture of streams 250 and 255 may be separately recycled for bromination in two separate C2 and C3+ bromination reactors. HBr stream 245 withdrawn from the HBr removal and product recovery unit 225 may be fed to the HBr oxidation unit 265 for recovery of elemental bromine. Liquid product stream 260 comprising C4+ hydrocarbons may also be withdrawn from the HBr removal and product recovery unit 225.

[0048] In the HBr oxidation unit 265, the separated HBr in HBr stream 245 may be oxidized with oxygen from stream 270 to produce elemental bromine and water. Stream 270 may comprise, for example, oxygen, air, or any other suitable source of oxygen. The water produced from oxidation of the HBr and coke may be withdrawn via first water stream 275. The elemental bromine may be withdrawn via bromine stream 205. Oxygen-depleted gas 280 may also be withdrawn from the HBr oxidation unit 265.

[0049] A portion 300 of the methane stream 235 recycled to the bromination stage 195 may also be fed to reactor-regenerator system 215 and used to strip the catalyst of heavier hydrocarbons. An inert gas stream 305, such as nitrogen, may also be fed to reactor-regenerator system 215 and used to displace methane from the catalyst prior to the circulated catalyst being oxidatively regenerated. An oxygen-containing stream 285 may also be introduced to reactor-regenerator system 215 for oxidative regeneration of the catalyst. The catalyst regeneration off-gas 295, leaving the reactor-regenerator system 215, which should comprise carbon oxides and which may also contain bromine and HBr may be routed to the HBr oxidation unit 265.

[0050] While FIG. 6 illustrates separation of the HBr while separating the hydrocarbon components into their respective fractions for product recovery and recycle, it should be understood that other suitable techniques for HBr separation and product recovery may also be used in accordance with embodiments of the present invention. For example, some embodiments may separate the HBr prior to separation of the hydrocarbon components into their respective fractions. Non-limiting examples of techniques for HBr separation include absorption of HBr into an aqueous solution, adsorption of HBr on a metal oxide, or electrolysis of the HBr to form elemental bromine. The hydrocarbons may then be fed to a product recovery unit wherein any suitable method of product recovery may be employed, including refrigerated condensation, cryogenic separation, or circulating absorption oil or some other solvent. In some embodiments, the hydrocarbons may first be dehydrated by a technique, such as solid-bed desiccant adsorption, prior to separation into their desired fractions.

[0051] Therefore, the present invention is well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed above are illustrative only, as the present invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Although individual embodiments are discussed, the invention covers all combinations of all those embodiments. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the present invention. All numbers and ranges disclosed above may vary by some amount. Whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any included range falling within the range are specifically disclosed.

CLAIMS

What is claimed is:

1. A process comprising:

reacting at least alkyl bromides over a catalyst in at least one conversion reactor
5 to produce at least an effluent stream comprising higher molecular weight hydrocarbons and hydrogen bromide;

removing a portion of the catalyst from the conversion reactor;

contacting the portion of the catalyst with a stripping gas to displace
hydrocarbons from the portion of the catalyst;

10 contacting the portion of the catalyst with a first inert gas;

contacting the portion the catalyst with oxygen to form a regenerated catalyst by
removal of coke;

contacting the regenerated catalyst with a second inert gas; and

15 introducing at least a portion of the regenerated catalyst into the conversion reactor.

2. The process of claim 1 wherein the catalyst comprises a crystalline aluminosilicate framework, and wherein the higher molecular weight hydrocarbons comprise hydrocarbons having six or more carbon atoms and the alkyl bromides comprise bromomethane.

20 3. The process of claim 1 wherein the alkyl bromides have a ratio of mono-brominated alkanes to mono-brominated alkanes plus di-brominated alkanes of equal to or greater than about 0.9.

4. The process of claim 1 wherein the portion of the catalyst removed from the conversion reactor comprises coke in an amount of equal to or greater than about 10
25 weight %.

5. The process of claim 1 wherein the stripping gas comprises at least one alkane selected from the group consisting of methane, ethane, propane, and any combination thereof.

6. The process of claim 1 wherein the stripping gas comprises hydrogen.

7. The process of claim 1 wherein the regenerated catalyst comprises coke in an amount of about 2 weight % to about 10 weight %.

8. The process of claim 1 wherein the regenerated catalyst comprise coke in an amount of less than about 0.1 weight %.

9. The process of claim 1 further comprising combining the stripping gas comprising the displaced hydrocarbons with the effluent stream from the conversion reactor, wherein the displaced hydrocarbons comprise hydrocarbons comprising six or more carbon atoms.

10. The process of claim 1:

wherein the stripping gas contacts the portion of the catalyst in an upper stripping stage;

wherein the first inert gas contacts the portion of the catalyst in a lower stripping stage; and

wherein a residence time of the catalyst in the upper stripping stage is greater than a residence time of the portion of the catalyst in the lower stripping stage.

11. The process of claim 1 wherein the contacting the portion the catalyst with oxygen is at a temperature of about 450°C to about 650°C.

12. The process of claim 1 wherein the conversion reactor comprises a moving bed of the catalyst, the catalyst having a particle size of about 1 millimeter to about 10 millimeters, and wherein the regenerated catalyst is introduced at or near a top of the conversion reactor.

13. The process of claim 12 wherein the catalyst is arranged in the conversion reactor in an annular bed.

14. The process of claim 1 further comprising:

cooling a slipstream of the effluent stream;

separating a gas stream from the cooled effluent stream;

combining the gas stream with the alkyl bromides; and

introducing the gas stream and the alkyl bromides to the conversion reactor.

15. The process of claim 1 further comprising:

removing hydrogen bromide from effluent stream;

oxidizing the hydrogen bromide to produce elemental bromine and water; and
reacting the elemental bromine with lower molecular alkanes to produce
additional alkyl bromides that are introduced into the conversion reactor.

16. The process of claim 15 wherein the removing the hydrogen bromide comprises
5 separating the effluent stream into at least a methane stream, an ethane stream, a
hydrogen bromide stream, a butane stream, and a liquid product stream, the liquid
product stream comprising hydrocarbons having four or more hydrocarbons.

17. A process comprising:

reacting at least bromomethane over a crystalline alumino-silicate catalyst in at
10 least one conversion reactor to produce at least an effluent stream comprising higher
molecular weight hydrocarbons and hydrogen bromide;

introducing a portion of the catalyst from the conversion reactor into a two-stage
stripping unit;

introducing a stripping gas into an upper stage of the two-stage stripping unit to
15 displace hydrocarbons from the portion of the catalyst, the hydrocarbons comprising
hydrocarbons having six or more carbon atoms;

introducing a first inert gas into a lower stage of the two-stage stripping unit to
remove a quantity of the stripping gas from the portion of the catalyst;

introducing the portion of the catalyst from the two-stage stripping unit into a
20 regeneration reactor to form a regenerated catalyst, wherein the portion of the catalyst
is contacted with an oxygen-containing stream for coke removal; and

introducing at least a portion of the regenerated catalyst into the conversion
reactor.

18. The process of claim 17 wherein the portion of the catalyst removed from the
25 conversion reactor comprises coke in an amount of equal to or greater than about 10
weight %, and wherein the regenerated catalyst comprise coke in an amount of about 2
weight % to about 10 weight %.

19. The process of claim 17 further comprising:

removing hydrogen bromide from the effluent stream in a hydrogen bromide
30 removal unit;

oxidizing the hydrogen bromide to produce elemental bromine and water; and
reacting the elemental bromine with lower molecular alkanes to produce
additional bromomethane that are introduced into the conversion reactor, the lower
molecular alkanes comprising recycled methane and feed methane that was fed to the
5 hydrogen bromide removal unit.

20. A reactor system comprising:

a conversion reactor configured for reaction of at least alkyl bromides over a
catalyst to produce at least a stream comprising higher molecular weight hydrocarbons
and hydrogen bromide;

10 a two-stage stripping unit configured to receive a portion of the catalyst from the
conversion reactor, the two-stage stripping unit comprising a first stripping stage
configured for contact of the portion of the catalyst with a stripping gas, and a second
stripping stage configured for contact of the portion of the catalyst with an inert gas;

a regeneration reactor configured for oxidation of the portion of the catalyst from
15 the two-stage stripping unit; and

a second stripping unit configured for contact of the portion of the catalyst from
the regeneration reactor with an inert gas.