

METHODS OF PRODUCING PROPYLENE AND ETHYLENE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is filed under the Patent Cooperation Treaty, which claims the benefit of priority to U.S. Provisional Application No. 62/577,525, filed on October 26, 2017, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] Methods are known for producing commercially important olefins, such as ethylene and propylene. Such methods include steam cracking, propane dehydrogenation, and various refinery catalytic cracking operations. Each of these procedures has one or more disadvantages. For example, propylene yields from steam cracking typically are not very high, and usually are not substantially improved by recycling. Also, purification of non-propylene products may be required, which can be costly, and such products usually have only fuel value. Propane dehydrogenation processes usually are characterized by rapid catalyst coking, which can require frequent, costly regenerations. Also, reasonable conversions typically require sub-atmospheric pressures, and propane can be difficult to separate from propylene. Moreover, propylene supplies from catalytic conversions are uncertain, and transportation and/or purification can present problems.

[0003] Also, many current chemical processes produce t-butyl alcohol and/or methyl t-butyl ether as side products.

[0004] Therefore, methods are desired that convert t-butyl alcohol and/or methyl t-butyl ether to ethylene and/or propylene, especially methods that do so in an efficient, cost-effective, and/or facile process.

SUMMARY OF THE INVENTION

[0005] Provided herein are methods of producing at least one of ethylene and propylene. In embodiments, the methods comprise providing a first mixture of C₄+ compounds; and contacting the first mixture of C₄+ compounds with a catalyst comprising a phosphorus treated zeolite to convert at least a portion of the first mixture of C₄+ compounds to at least one of ethylene and propylene. The first mixture of C₄+ compounds may include at least one of t-butyl alcohol and methyl t-butyl ether. In one embodiment, the methods further comprise separating the ethylene and/or the propylene from the first mixture of C₄+ compounds to form a second mixture of C₄+ compounds, and contacting the second mixture of C₄+ compounds with the catalyst to convert at

least a portion of the second mixture of C4+ compounds to at least one of ethylene and propylene. In another embodiment, the methods further comprise contacting the first mixture of C4+ compounds comprising at least one of t-butyl alcohol and methyl t-butyl ether with the catalyst.

DETAILED DESCRIPTION OF THE INVENTION

[0006] Provided herein are methods for producing at least one of ethylene and propylene from a mixture of C4+ compounds that overcome one or more of the disadvantages associated with other methods for producing commercially important olefins.

[0007] The mixture of C4+ compounds may be contacted with a catalyst comprising a phosphorus treated zeolite to convert at least a portion of the mixture of C4+ compounds to at least one of ethylene and propylene. The ethylene and/or propylene then may be separated from the mixture of C4+ compounds, and the mixture of C4+ compounds may be contacted with the catalyst a second time. In addition to the ethylene and/or propylene, other, non-C4+ compounds, including, but not limited to, coke, C₂H₆, and C₃H₈, may be removed from the mixture after one or more of the contacting steps. Alternatively, the mixture of C4+ compounds may be contacted with the catalyst a second time without removing ethylene and/or propylene from the mixture. The contacting step may be repeated any number of times. In one embodiment, the contacting step is repeated until a desired conversion rate of the mixture of C4+ compounds, or a portion thereof, to at least one of propylene and ethylene is achieved.

[0008] Generally, the mixture of C4+ compounds may be contacted with a catalyst comprising phosphorus treated zeolite at any combination of temperature and pressure that is effective to convert at least a portion of the mixture of C4+ compounds to at least one of ethylene and propylene. In one embodiment, the contacting occurs at a temperature of about 600 °F to about 1,200 °F. In another embodiment, the contacting occurs at a temperature of about 700 °F to about 1,050 °F. In a further embodiment, the contacting occurs at a temperature of about 700 °F to about 950 °F. In yet another embodiment, the contacting occurs at a temperature of about 700 °F to about 850 °F. In a still further embodiment, the contacting occurs at a temperature of about 700 °F to about 750 °F. In additional embodiments, the contacting occurs at a temperature of about 800 °F to about 1,050 °F. In some embodiments, the contacting occurs at a temperature of about 900 °F to about 1,050 °F. In further embodiments, the contacting occurs at a temperature of about 1,000 °F to about 1,050 °F.

[0009] In one embodiment, the contacting occurs at ambient pressure. In another embodiment, the contacting occurs at a pressure of about 1 psig to about 20 psig. In yet another embodiment, the contacting occurs at a pressure of about 5 psig to about 15 psig. In a still further

embodiment, the contacting occurs at a pressure of about 8 psig to about 12 psig. In an additional embodiment, the contacting occurs at a pressure of about 10 psig.

[0010] In one embodiment, the contacting occurs at a temperature of about 600 °F to about 1,200 °F, about 700 °F to about 1,050 °F, about 700 °F to about 950 °F, about 700 °F to about 850 °F, about 700 °F to about 750 °F, about 800 °F to about 1,050 °F, about 900 °F to about 1,050 °F, or about 1,000 °F to about 1,050 °F, and at ambient pressure.

[0011] In one embodiment, the contacting occurs at a temperature of about 600 °F to about 1,200 °F, about 700 °F to about 1,050 °F, about 700 °F to about 950 °F, about 700 °F to about 850 °F, about 700 °F to about 750 °F, about 800 °F to about 1,050 °F, about 900 °F to about 1,050 °F, or about 1,000 °F to about 1,050 °F, and a pressure of about 1 psig to about 20 psig.

[0012] In one embodiment, the contacting occurs at a temperature of about 600 °F to about 1,200 °F, about 700 °F to about 1,050 °F, about 700 °F to about 950 °F, about 700 °F to about 850 °F, about 700 °F to about 750 °F, about 800 °F to about 1,050 °F, about 900 °F to about 1,050 °F, or about 1,000 °F to about 1,050 °F, and a pressure of about 5 psig to about 15 psig.

[0013] In one embodiment, the contacting occurs at a temperature of about 600 °F to about 1,200 °F, about 700 °F to about 1,050 °F, about 700 °F to about 950 °F, about 700 °F to about 850 °F, about 700 °F to about 750 °F, about 800 °F to about 1,050 °F, about 900 °F to about 1,050 °F, or about 1,000 °F to about 1,050 °F, and a pressure of about 8 psig to about 12 psig.

[0014] In one embodiment, the contacting occurs at a temperature of about 600 °F to about 1,200 °F, about 700 °F to about 1,050 °F, about 700 °F to about 950 °F, about 700 °F to about 850 °F, about 700 °F to about 750 °F, about 800 °F to about 1,050 °F, about 900 °F to about 1,050 °F, or about 1,000 °F to about 1,050 °F, and a pressure of about 10 psig.

[0015] The hydrocarbon feed weight hourly space velocity (based on the zeolite component of the catalyst) may be about 1 to about 750 hr⁻¹, about 1 to about 500 hr⁻¹, about 1 to about 400 hr⁻¹, about 200 to about 400 hr⁻¹, about 300 to about 400 hr⁻¹, or about 316 hr⁻¹.

Mixture of C₄+ Compounds

[0016] In embodiments, the mixture of C₄+ compounds comprises at least one of t-butyl alcohol and methyl t-butyl ether. In one embodiment, the mixture of C₄+ compounds comprises t-butyl alcohol. In another embodiment, the mixture of C₄+ compounds comprises methyl t-butyl ether. In yet another embodiment, the mixture of C₄+ compounds comprises methyl t-butyl ether and t-butyl alcohol.

[0017] The mixture of C4+ compounds may be a tailstream, or part of a tailstream, of a chemical process, such as a methanol-to-olefin process.

[0018] The mixture of C4+ compounds may be part of a feed stream that includes a diluent. The diluent, in embodiments, is present in the feed stream in an amount of about 10 % to about 40 % by weight of the mixture of C4+ compounds, about 15 % to about 35 % by weight of the C4+ compounds, about 20 % to about 35 % by weight of the C4+ compounds, about 25 % to about 35 % by weight of the C4+ compounds, or about 30 % by weight of the mixture of C4+ compounds. In one embodiment, the diluent comprises steam.

Conversion Rates

[0019] Unless otherwise noted, the “conversion rates” provided herein are those obtained after a contacting step, as described herein, is performed once, and the contact step may be the first contacting step, second contacting step, etc. Higher cumulative conversion rates may be achieved by repeating the contacting step one or more times, as described herein.

[0020] In embodiments, the mixture of C4+ compounds comprises t-butyl alcohol, and the weight percentage of the t-butyl alcohol converted to ethylene is about 2 to about 50, about 2 to about 40, about 2 to about 30, 2 to about 20, about 2 to about 15, about 2 to about 10, about 2 to about 8, about 2 to about 6, or about 4 to about 6, or about 4 to about 5.

[0021] In embodiments, the mixture of C4+ compounds comprises t-butyl alcohol, and the weight percentage of the t-butyl alcohol converted to propylene is about 10 to about 50, about 10 to about 40, about 10 to about 30, about 15 to about 30, about 15 to about 25, about 20 to about 25, or about 22 to about 24.

[0022] In embodiments, the mixture of C4+ compounds comprises t-butyl alcohol, and the weight percentage of the t-butyl alcohol converted to at least one of propylene and ethylene is about 15 to about 60, about 15 to about 50, about 15 to about 40, about 20 to about 40, about 20 to about 35, about 20 to about 30, or about 25 to about 30.

[0023] In embodiments, the mixture of C4+ compounds comprises methyl t-butyl ether, and the weight percentage of the methyl t-butyl ether converted to ethylene is about 2 to about 50, about 2 to about 40, about 2 to about 30, 2 to about 20, about 2 to about 15, about 2 to about 10, about 2 to about 8, about 2 to about 6, or about 4 to about 6, or about 4 to about 5.

[0024] In embodiments, the mixture of C4+ compounds comprises methyl t-butyl ether, and the weight percentage of the methyl t-butyl ether converted to propylene is about 10 to about 50, about 10 to about 40, about 10 to about 30, about 15 to about 30, about 15 to about 25, about 20 to about 25, or about 22 to about 24.

[0025] In embodiments, the mixture of C4+ compounds comprises methyl t-butyl ether, and the weight percentage of the methyl t-butyl ether converted to at least one of propylene and ethylene is about 15 to about 60, about 15 to about 50, about 15 to about 40, about 20 to about 40, about 20 to about 35, about 20 to about 30, or about 25 to about 30.

[0026] In embodiments, the mixture of C4+ compounds comprises t-butyl alcohol, and at least 20 weight %, at least 22 weight %, at least 25 weight %, at least 30 weight %, at least 35 weight %, at least 40 weight %, at least 45 weight %, or at least 50 % of the t-butyl alcohol is converted to at least one of ethylene and propylene.

[0027] In embodiments, the mixture of C4+ compounds comprises t-butyl alcohol, and at least 20 weight %, at least 22 weight %, at least 25 weight %, at least 30 weight %, at least 35 weight %, at least 40 weight %, at least 45 weight %, or at least 50 % of the t-butyl alcohol is converted to propylene.

[0028] In embodiments, the mixture of C4+ compounds comprises t-butyl alcohol, and at least 2 weight %, at least 5 weight %, at least 10 weight %, at least 20 weight %, at least 25 weight %, at least 30 weight %, at least 40 weight %, or at least 50 % of the t-butyl alcohol is converted to ethylene.

[0029] In embodiments, the mixture of C4+ compounds comprises methyl t-butyl ether, and at least 20 weight %, at least 22 weight %, at least 25 weight %, at least 30 weight %, at least 35 weight %, at least 40 weight %, at least 45 weight %, or at least 50 % of the methyl t-butyl ether is converted to at least one of ethylene and propylene.

[0030] In embodiments, the mixture of C4+ compounds comprises methyl t-butyl ether, and at least 10 weight %, at least 20 weight %, at least 25 weight %, at least 30 weight %, at least 35 weight %, at least 40 weight %, at least 45 weight %, or at least 50 % of the methyl t-butyl ether is converted to propylene.

[0031] In embodiments, the mixture of C4+ compounds comprises methyl t-butyl ether, and at least 2 weight %, at least 5 weight %, at least 10 weight %, at least 20 weight %, at least 35 weight %, at least 40 weight %, at least 45 weight %, or at least 50 % of the methyl t-butyl ether is converted to ethylene.

Catalysts

[0032] Generally, the catalysts provided herein include phosphorus treated zeolite catalysts. In embodiments, the phosphorus treated zeolite comprises phosphorus in an amount of about 0.1 % to about 10 %, by weight of the zeolite, about 0.1 % to about 8 %, by weight of the zeolite, about 0.1 % to about 6 %, by weight of the zeolite, about 0.1 % to about 5 % by weight of the zeolite, about 1

% to about 4 %, by weight of the zeolite, about 1 % to about 3 %, by weight of the zeolite, or about 1.2 %, by weight of the zeolite.

[0033] The phosphorus treated zeolite may be made by contacting a zeolite, which may be a powder, with a phosphorus containing compound. The phosphorus containing compound may be an acid. Examples of phosphorus containing compounds include, but are not limited to, H_3PO_4 , ammonium hydrogen phosphates, such as $(\text{NH}_4)_2\text{HPO}_4$ or $(\text{NH}_4)\text{H}_2\text{PO}_4$, phosphonic acid (also called phosphorus acid) H_3PO_3 , phosphorus pentoxide (P_2O_5), or a combination thereof. The zeolite may be contacted with the phosphorus containing compound in an amount sufficient to impart the catalyst with a desired phosphorus content. The zeolite may be contacted with water before, during, or after the zeolite is contacted with the phosphorus containing compound. The amount of water may be an amount sufficient to wet the zeolite only. After being contacted with a phosphorus containing compound and/or water, the zeolite may be dried by any means known in the art.

[0034] The phosphorus treated zeolite may be combined with a binder. The binder may include silica, kaolin, calcium, bentonite, alumina, silica aluminate, or a combination thereof. In one embodiment, the binder includes bentonite clay, silica, and kaolin. The bentonite clay, silica, and kaolin may be present in the binder at a weight ratio of about 1:(8-16):(20-28); about 1:(10-14):(22-26); or about 1:12:24.

[0035] The phosphorus treated zeolite, in embodiments, is present in the catalyst in an amount of about 1 % to about 50 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder. In further embodiments, the phosphorus treated zeolite is present in the catalyst in an amount of about 5 % to about 40 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder. In additional embodiments, the phosphorus treated zeolite is present in the catalyst in an amount of about 5 % to about 30 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder. In a particular embodiment, the phosphorus treated zeolite is present in the catalyst in an amount of about 10 % to about 25 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder. In some embodiments, the phosphorus treated zeolite is present in the catalyst in an amount of about 15 % to about 30 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder. In particular embodiments, the phosphorus treated zeolite is present in the catalyst in an amount of about 20 % to about 30 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder. In one embodiment, the phosphorus treated zeolite is present in the catalyst in an amount of about 25 % by weight, based on the combined weight of the phosphorus treated zeolite and the binder.

[0036] The phosphorus treated zeolite and binder may be contacted with an amount of water sufficient to form a paste, and the paste may be mixed by any means known in the art in order to form a paste that is at least substantially homogeneous.

[0037] The at least substantially homogeneous paste may be extruded into extrudates of any desired size. The extrudates also may be calcined, steamed, or a combination thereof. The calcining may be performed at a temperature of about 500 °C to about 700 °C, or about 600 °C. The steam treatment, in one embodiment, is conducted prior to contacting the catalyst with a mixture of C4+ hydrocarbons. The steam treatment may be performed at a temperature of about 800 °F to about 1200 °F, 500 °C to 700 °C, or about 550 °C to about 600 °C, and at a pressure of about 1 to about 5 atmospheres, or about 1.5 to about 3 atmospheres, for about 1 to about 48 hours, or about 15 to about 30 hours.

[0038] The extrudates generally may have any desired size. For lab testing, the extrudates may have a size of 6 to 20 mesh. In one embodiment, the catalyst is a fixed bed catalyst, and the extrudates are particles having an average diameter of about 2 mm to 5 mm. The particles may be at least substantially spherical, but the use of the term “diameter” is not intended to convey that the particles necessarily are or include at least substantially spherical particles. When particles are not at least substantially spherical, the term “diameter” refers to the average largest dimension of particles.

[0039] The term “zeolite”, as used herein, generally refers to porous materials, such as hydrated, crystalline metal aluminosilicates, and/or molecular sieves of a non-zeolitic material. Thus, zeolites include a group of natural or synthetic hydrated aluminosilicate minerals that contain alkali and alkaline metals. Zeolites may be characterized by a framework structure that encloses interconnected cavities occupied by ion-exchangeable large metal cations, such as potassium and water molecules permitting reversible dehydration.

[0040] In embodiments, the zeolite comprises a network of SiO₄ and AlO₄ tetrahedra in which aluminum and silicon atoms are crosslinked in a three-dimensional framework by sharing oxygen atoms. In the framework, the ratio of oxygen atoms to the total of aluminum and silicon atoms may be equal to about 2. The framework may exhibit a negative electrovalence that can be balanced by the inclusion of cations within the crystal. The cations may include potassium cations, ammonium cations, or a combination thereof.

[0041] The formula of the zeolite may vary without changing the crystalline structure. In an embodiment, the mole ratio of silicon dioxide to aluminum oxide (SiO₂/Al₂O₃) in the zeolite may vary from about 10 to about 200. In one embodiment, the molar SiO₂:Al₂O₃ ratio is about 20 to about 60.

[0042] In one embodiment, the zeolite has an alkali metal content of less than about 0.5 % by weight of the zeolite. Alkali metals are those in Group IA or Group IIA of the periodic table, such as lithium, sodium, potassium, calcium, etc.

[0043] In embodiments, the zeolite is selected from ZSM-5, ZSM-11, ZSM-22, ZSM-23, ZSM-35, ZSM-48, ZSM-57, SUZ-4, SSZ-23; SSZ-25; SSZ-28, SSZ-32, SSZ-36, ZSM-3, ZSM-4, ZSM-10, ZSM-12, ZSM-20, zeolite beta, zeolite omega, zeolite L, zeolite X, zeolite Y, REY, USY, RE-USY, mordenite, LZ-210, LZ-210-M, LZ-210-T, LZ-210-A, SSZ-24, SSZ-26, SSZ-31, SSZ-33, SSZ-35, SSZ-37, SSZ-41, SSZ-42, SSZ-44, MCM-58, or a combination thereof. In one embodiment, the zeolite is ZSM-5.

[0044] In embodiments, the catalyst comprises a phosphorus treated ZSM-5 zeolite. In one embodiment, the catalyst comprises a phosphorus treated ZSM-5 zeolite having a molar $\text{SiO}_2:\text{Al}_2\text{O}_3$ ratio of about 20 to about 60. In another embodiment, the catalyst comprises a phosphorus treated ZSM-5 zeolite having an alkali metal content of less than about 0.5 % by weight of the ZSM-5 zeolite.

[0045] In embodiments, the catalyst is a fixed bed catalyst. In another embodiment, the catalyst is a liquid catalyst.

EXAMPLES

[0046] The present invention is further illustrated by the following examples, which are not to be construed in any way as imposing limitations upon the scope thereof. On the contrary, it is to be clearly understood that resort may be had to various other aspects, embodiments, modifications, and equivalents thereof which, after reading the description herein, may suggest themselves to one of ordinary skill in the art without departing from the spirit of the present invention or the scope of the appended claims. Thus, other aspects of this invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein.

Example 1 – Preparation of Catalyst

[0047] To 200 g of CBV5524G zeolite powder (Zeolyst, USA), H_3PO_4 and water were added. The H_3PO_4 was added in an amount sufficient to provide an equivalent of 1.2 % by weight phosphorus, based on the weight of the dry zeolite powder. Water was added in an amount sufficient to wet the powder barely (incipient wetness). The zeolite powder was then dried overnight at 120 °C.

[0048] To the zeolite powder was added 16 g of bentonite clay, 202 g of Davison 633 silica gel (VWR, USA), 388 g of kaolin, and an amount of DI water sufficient to make a viscous paste. These components were then mixed with a mixer (Caleva) to form a homogeneous paste.

[0049] The paste was then extruded into 2 mm OD extrudates with a high torque extruder (Bonnot BA373). The extrudates were then calcined at 600 °C in air, and then steamed for 24 hours at 575 °C.

Example 2 – Conversion of t-Butyl Alcohol

[0050] The catalyst of Example 1 was configured as a fixed bed catalyst through which vaporized t-butyl alcohol (TBA) was fed at 1 atm, 1050 °F, and a weight hourly space velocity of 316 hr⁻¹.

[0051] The conversion of the TBA was 99.8 %, and the product selectivities are shown in the following table:

Table 1- Product Selectivity of Example 2

Component	Selectivity (g / 100 g TBA converted)
Coke	0.06
CO ₂	0.03
H ₂	0.02
CH ₄	0.08
C ₂ H ₄	4.73
C ₂ H ₆	0.07
C ₃ H ₆	22.57
C ₃ H ₈	1.48
Isobutane	1.48
n-Butane	1.03
C4 olefins	51.98
C5 olefins	11.12
C5 paraffins	0.85
C6+	4.5

[0052] The C4+ products, including isobutane, n-butane, C4 olefins, C5 olefins, C5 paraffins, and C6+ products, then may be recycled to produce more ethylene and/or propylene.

CLAIMS

What is claimed is:

1. A method of producing at least one of ethylene and propylene, the method comprising:
providing a first mixture of C₄⁺ compounds; and
contacting the first mixture of C₄⁺ compounds with a catalyst comprising:
 - (a) a phosphorus treated zeolite, wherein the phosphorus treated zeolite comprises an alkali metal, and wherein the alkali metal is present in an amount no greater than 0.5 % by weight of the phosphorus treated zeolite, and
 - (b) a binder, wherein the binder comprises bentonite clay, silica and kaolin and wherein the bentonite clay, silica and kaolin are present in the binder in a bentonite clay:silica:kaolin weight ratio of 1:8-16:20-28;to convert at least a portion of the first mixture of C₄⁺ compounds to at least one of ethylene and propylene, thereby producing a first effluent comprising at least one of ethylene and propylene
wherein the first mixture of C₄⁺ compounds comprises at least one of t-butyl alcohol and methyl t-butyl ether.
2. The method of claim 1, further comprising separating the ethylene and/or the propylene from the first effluent to form a second mixture of C₄⁺ compounds, and contacting the second mixture of C₄⁺ compounds with the catalyst to convert at least a portion of the second mixture of C₄⁺ compounds to at least one of ethylene and propylene.
3. The method of claim 1 wherein the first mixture of C₄⁺ compounds comprises the t-butyl alcohol, and at least 20 weight % of the t-butyl alcohol is converted to at least one of ethylene and propylene.
4. The method of claim 3, wherein at least 22 weight % of the t-butyl alcohol is converted to propylene.

5. The method of claim 1 wherein the first mixture of C₄⁺ compounds comprises the methyl t-butyl ether, and at least 20 weight % of the methyl t-butyl ether is converted to at least one of ethylene and propylene.
6. The method of claim 5, wherein at least 22 weight % of the methyl t-butyl ether is converted to propylene.
7. The method of claim 1 wherein the phosphorus treated zeolite comprises a ZSM-5 zeolite.
8. The method of claim 7, wherein the ZSM-5 zeolite has an alkali metal content of 0.5 % by weight of the ZSM-5 zeolite.
9. The method of claim 1 wherein the phosphorus treated zeolite comprises phosphorus in an amount of 0.1 % to 10 % by weight of the phosphorus treated zeolite.
10. The method of claim 1 wherein the phosphorus treated zeolite comprises phosphorus in an amount of 1 % to 3 % by weight of the phosphorus treated zeolite.
11. The method of claim 1, wherein the binder further comprises calcium, alumina, silica aluminate, or a combination thereof.
12. The method of claim 1 wherein the contacting occurs at ambient pressure.
13. The method of claim 1 wherein the contacting occurs at a pressure of 1 psig (6894.7 Pa) to 20 psig (137895 Pa).
14. The method of claim 1 wherein the contacting occurs at a temperature of 600 °F (315.5 °C) to 1,200 °F (648.8 °C).
15. The method of claim 1 further comprising steaming the catalyst prior to contacting the first mixture of C₄⁺ compounds with the catalyst.
16. The method of claim 15, wherein the steaming is performed at a temperature of 800 °F (426.6 °C) to 1200 °F (648.8 °C).
17. The method of claim 2, wherein the first mixture of C₄⁺ compounds and/or the second mixture of C₄⁺ compounds is diluted with steam.

18. The method of claim 17, wherein the first mixture of C₄⁺ compounds and/or the second mixture of C₄⁺ compounds is diluted with 20 to 35 % by weight of steam, based on the weight of the first mixture of C₄⁺ compounds and/or the second mixture of C₄⁺ compounds, respectively.