

DUAL CATALYST SYSTEM FOR PROPYLENE PRODUCTION

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 62/188,178 filed July 2, 2015.

TECHNICAL FIELD

[0002] Embodiments of the present disclosure generally relate to propylene production via metathesis reactions, and more specifically relate to converting butene to propylene using a dual catalyst system comprising metathesis and cracking catalysts.

BACKGROUND

[0003] In recent years, there has been a dramatic increase in the demand for propylene to feed the growing markets for polypropylene, propylene oxide and acrylic acid. Currently, most of the propylene produced worldwide (74 million tons/year) is a by-product from steam cracking units (57%) which primarily produce ethylene, or a by-product from Fluid Catalytic Cracking (FCC) units (30%) which primarily produce gasoline. These processes cannot respond adequately to a rapid increase in propylene demand.

[0004] Other propylene production processes contributes about 12% of total propylene production. Among these processes are propane dehydrogenation (PDH), metathesis reactions requiring both ethylene and butene, high severity FCC, olefins cracking and methanol to olefins (MTO). However, propylene demand has exceeded ethylene and gasoline/distillate demand, and propylene supply has not kept pace with this increase in propylene demand.

SUMMARY

[0005] Accordingly, ongoing needs exist for improved processes for the selective production of propylene using dual catalyst systems. Embodiments of the present disclosure are directed to propylene production from butenes via a dual catalyst system.

[0006] In one embodiment, a process for the production of propylene is provided. The process comprises providing a dual catalyst system comprising: a mesoporous silica catalyst impregnated with metal oxide, and a mordenite framework inverted (MFI) structured silica catalyst downstream of the mesoporous silica catalyst. The mesoporous silica catalyst includes a total pore volume of at least about 0.600 cm³/g, and the MFI structured silica catalyst includes a total acidity of 0.001 mmol/g to 0.1 mmol/g. The process also comprises producing propylene from a stream comprising butene via metathesis and cracking by contacting the stream comprising butene with the dual catalyst system, where the stream comprising butene contacts the mesoporous silica catalyst before contacting the MFI structured silica catalyst.

[0007] In another embodiment, a dual catalyst system for producing propylene from butene is provided. The dual catalyst system comprises a metathesis catalyst zone and a cracking catalyst zone downstream of the metathesis catalyst zone. The metathesis catalyst zone comprises mesoporous silica catalyst impregnated with metal oxide, where the mesoporous silica catalyst includes a pore size distribution of at least 2.5 nm to 40 nm and a total pore volume of at least 0.600 cm³/g. The cracking catalyst zone comprises a mordenite framework inverted (MFI) structured silica catalyst, where the MFI structured silica catalyst includes a pore size distribution of at least 1.5 nm to 3 nm, and a total acidity of 0.001 mmol/g to 0.1 mmol/g.

[0008] Additional features and advantages of the described embodiments will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the described embodiments, including the detailed description which follows, the claims, as well as the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 is an X-ray Powder Diffraction (XRD) graph illustrating the XRD profile of a CARiACT Q10 support, and a CARiACT Q10 support impregnated with WO₃ at a molar ratio of silica/WO₃ equal to approximately 10 in accordance with one or more embodiments of the present disclosure.

[0010] FIG. 2 is an XRD graph of a MFI-2000 catalyst.

[0011] FIG. 3 is a Scanning Electron Microscopy (SEM) image of a CARiACT Q10 support.

[0012] FIG. 4 is an SEM image of a CARiACT Q10 support impregnated with 10% by weight WO_3 in accordance with one or more embodiments of the present disclosure.

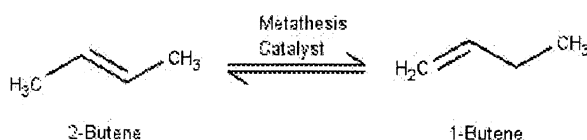
[0013] FIG. 5 is an SEM image of a of MFI-2000 catalyst.

DETAILED DESCRIPTION

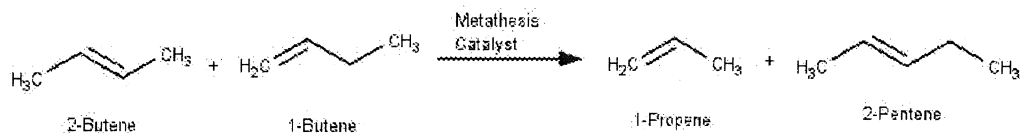
[0014] Embodiments of the present disclosure are directed to systems and methods for converting a stream comprising butene to a stream comprising propylene via catalyzed metathesis and catalyzed cracking. Specifically, the present embodiments are related to a two-stage catalyst system containing metathesis and cracking catalysts for greater propylene ($\text{C}_3=$) production from a butene stream. In operation, the metathesis catalyst is followed by the cracking catalyst to provide a greater yield of propylene, and optionally a greater combined yield of propylene and ethylene.

[0015] As shown in the following Formulas 1 and 2, “metathesis” or “self-metathesis” is generally a two-step process: 2-butene isomerization and then cross-metathesis using the metathesis catalyst system. As shown in the following Formula 3, “catalyzed cracking” refers to the conversion of $\text{C}_4\text{-C}_6$ alkenes to propylene and other alkanes and/or alkenes, for example, $\text{C}_1\text{-C}_2$ alkenes.

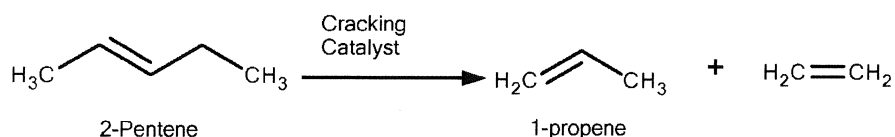
[0016] Formula 1: 2-Butene Isomerization



[0017] Formula 2: Cross-Metathesis



[0018] Formula 3: Catalytic Cracking



[0019] Referring to Formulas 1-3, the “metathesis” and “catalytic cracking” reactions are not limited to these reactants and products; however, Formulas 1-3 provide a basic illustration of the reaction methodology. As shown in Formulas 1 and 2, metathesis reactions take place between two alkenes. The groups bonded to the carbon atoms of the double bond are exchanged between the molecules to produce two new alkenes with the swapped groups. The specific catalyst that is selected for the olefin metathesis reaction may generally determine whether a cis-isomer or trans-isomer is formed, as the coordination of the olefin molecules with the catalyst play an important role, as do the steric influences of the substituents on the double bond of the newly formed molecule.

[0020] The present dual catalyst system comprises: a mesoporous silica catalyst, which is a mesoporous silica catalyst support impregnated with metal oxide; and a mordenite framework inverted (MFI) structured silica catalyst downstream of the mesoporous silica catalyst. Various structures are contemplated for the mesoporous silica catalyst support, for example, a molecular sieve. As used in the application, “mesoporous” means that the silica support has a narrow pore size distribution. Specifically, the mesoporous silica catalyst includes a narrow pore size distribution of from about 2.5 nm to about 40 nm and a total pore volume of at least about 0.600 cm³/g. Without being bound by theory, the present pore size distribution and pore volume are sized to achieve better catalytic activity and reduced

blocking of pores by metal oxides, whereas smaller pore volume and pore size catalyst systems are susceptible to pore blocking and thereby reduced catalytic activity.

[0021] Moreover, utilizing an MFI structured silica catalyst downstream of the mesoporous silica catalyst surprisingly provides the best yield of propylene from a butene stream. The person of ordinary skill in the art would have expected the best yield by first cracking butene to propylene and then cracking any remaining butene via metathesis. However, it was surprisingly found that propylene yield is increased, and additionally the combined yield of propylene and ethylene is increased by placing the MFI structured silica catalyst downstream of the mesoporous silica catalyst.

[0022] In one or more embodiments, the pore size distribution of the mesoporous silica catalyst may range from about 2.5 nm to about 40 nm, or about 2.5 nm to about 20 nm, or about 2.5 nm to about 4.5 nm, or about 2.5 nm to about 3.5 nm, or about 8 nm to about 18 nm, or about 12 nm to about 18 nm. In further embodiments, the total pore volume may be from about 0.600 cm³/g to about 2.5 cm³/g, or about 0.600 cm³/g to about 1.5 cm³/g, or about 0.600 cm³/g to about 1.3 cm³/g, or about 0.600 cm³/g to about 0.800 cm³/g, or about 0.600 cm³/g to about 0.700 cm³/g, or about 0.900 cm³/g to about 1.3 cm³/g.

[0023] Moreover, while broader ranges are contemplated, the mesoporous silica catalyst may, in one or more embodiments, include a surface area of about 250 meters²/gram (m²/g) to about 600 m²/g. In further embodiments, the mesoporous silica catalyst may have a surface area of from about 450 m²/g to about 600 m²/g, or about 250 m²/g to about 350 m²/g, or about 275 m²/g to about 325 m²/g, or about 275 m²/g to about 300 m²/g. Further, the mesoporous silica catalyst may have a total acidity of up to about 0.5 millimole/gram (mmol/g), or about 0.01 mmol/g to about 0.5 mmol/g, or about 0.1 mmol/g to about 0.5 mmol/g, or about 0.3 mmol/g to about 0.5 mmol/g, or about 0.4 mmol/g to about 0.5 mmol/g. Acidity is generally maintained at or less than about 0.5 mmol/g to yield the desired selectivity of propylene and reduced production of undesirable byproducts such as aromatics. Increasing acidity may increase the overall butene conversion; however, this increased conversion may lead to less selectivity and increased production of aromatic byproducts, which can lead to catalyst coking and deactivation.

[0024] Furthermore, the mesoporous silica catalyst may have a particle size of from about 20 nm to about 200 nm, or about 50 nm to about 150 nm, or about 75 nm to about 125 nm. In additional embodiments, the mesoporous silica catalyst may have an individual crystal size of about 1 μm to about 100 μm , or about 10 μm to about 40 μm .

[0025] Various formulations for the mesoporous silica support, as well as methods of making the formulation, are contemplated. For example, the mesoporous silica catalyst support may be produced via wet impregnation, hydrothermal synthesis, or both. Additionally, the mesoporous silica catalyst support may be characterized by an ordered pore structure. For example, this ordered structure may have a hexagonal array of pores. One suitable embodiment of a mesoporous silica support with a hexagonal pore array may be the Santa Barbara Amorphous (SBA-15) mesoporous silica molecular sieve. Alternatively, another suitable embodiment of a mesoporous silica support is the CARiACT Q-10 (Q-10) spherical catalyst support produced by Fuji Silysia Chemical Ltd.

[0026] The catalyst of the metathesis reaction is the impregnated metal oxide of the silica support. The metal oxide may comprise one or oxides of a metal from the Groups 6-10 of the IUPAC Periodic Table. In one or more embodiments, the metal oxide may be an oxide of molybdenum, rhenium, tungsten, or combinations thereof. In a specific embodiment, the metal oxide is tungsten oxide (WO_3). It is contemplated that various amounts of metal oxide may be impregnated into the mesoporous silica catalyst support. For example and not by way of limitation, the molar ratio of silica to metal oxide, for example, WO_3 , is about 5 to about 60, or about 5 to about 15, or about 20 to about 50, or about 20 to about 40, or about 25 to about 35.

[0027] Additionally, various silica structures are contemplated for the MFI structured silica catalyst. For example, the MFI structured silica catalyst may include MFI structured aluminosilicate zeolite catalysts or MFI structured silica catalysts free of alumina. As used herein, “free” means less than 0.001% by weight of alumina in the MFI structured silica catalyst. Moreover, it is contemplated that the MFI structured silica catalyst may include other impregnated metal oxides in addition to or as an alternative to alumina. Like the mesoporous silica catalyst, the MFI structured catalysts may have alumina, metal oxides, or both impregnated in the silica support. In addition to or as a substitute for alumina, it is

contemplated to include the metal oxides listed prior, specifically, one or more oxides of a metal from Groups 6-10 of the IUPAC Periodic Table, more specifically, metal oxides of molybdenum, rhenium, tungsten, titanium, or combinations thereof.

[0028] For the MFI structured aluminosilicate zeolite catalysts, various amounts of alumina are contemplated. In one or more embodiments, the MFI structured aluminosilicate zeolite catalysts may have a molar ratio of silica to alumina of about 5 to about 5000, or about 100 to about 4000, or about 200 to about 3000, or about 1500 to about 2500, or about 1000 to about 2000. Various suitable commercial embodiments of the MFI structured aluminosilicate zeolite catalysts are contemplated, for example, ZSM-5 zeolites such as MFI-280 produced by Zeolyst International or MFI-2000 produced by Saudi Aramco.

[0029] Various suitable commercial embodiments are also contemplated for the alumina free MFI structured catalysts. One such example is Silicalite-1 produced by Saudi Aramco.

[0030] The MFI structured silica catalyst may include a pore size distribution of from about 1.5 nm to 3 nm, or about 1.5 nm to 2.5 nm. Furthermore, the MFI structured silica catalyst may have a surface area of from about 300 m²/g to about 425 m²/g, or about 340 m²/g to about 410 m²/g. Additionally, the MFI structured silica catalyst may have a total acidity of from about 0.001 mmol/g to about 0.1 mmol/g, or about 0.01 mmol/g to about 0.08 mmol/g. The acidity is maintained at or less than about 0.1 mmol/g in order to reduce production of undesirable byproducts such as aromatics. Increasing acidity may increase the amount of cracking; however, this increased cracking may also lead to less selectivity and increased production of aromatic byproducts, which can lead to catalyst coking and deactivation.

[0031] In some cases, MFI structured silica catalyst may be modified with an acidity modifier to adjust the level of acidity in the MFI structured silica catalyst. For example, these acidity modifiers may include rare earth modifiers, phosphorus modifiers, potassium modifiers, or combinations thereof. However, as the present embodiments are focused on reducing the acidity to a level at or below 0.1 mmol/g, the present structured silica catalyst may be free of acidity modifier, such as those selected from rare earth modifiers, phosphorus modifiers, potassium modifiers, or combinations thereof. As used herein, "free of acidity

modifiers” means less than 0.001% by weight of acidity modifier in the MFI structured silica catalyst.

[0032] Further, the MFI structured silica catalyst may have a pore volume of from about 0.1 cm³/g to about 0.3 cm³/g, or about 0.15 cm³/g to about 0.25 cm³/g. Additionally, the MFI structured silica catalyst may have an individual crystal size ranging from about 10 nm to about 40 μm, or from about 15 μm to about 40 μm, or from about 20 μm to about 30 μm. In another embodiment, the MFI structured silica catalyst may have an individual crystal size in a range of from about 1 μm to about 5 μm.

[0033] Moreover, various amounts of each catalyst are contemplated for the present dual catalyst system. For example, it is contemplated that the ratio by volume of metathesis catalyst to cracking catalyst may range from about 5:1 to about 1:5, or about 2:1 to about 1:2, or about 1:1.

[0034] In operation, a product stream comprising propylene is produced from a butene containing stream via metathesis conversion by contacting the butene stream with the dual catalyst system. The butene stream may comprise 2-butene, and optionally comprises one or more isomers, such as 1-butene, trans-2-butene, and cis-2-butene. The present discussion centers on butene based feed streams; however, it is known that other C₁-C₆ components may also be present in the feed stream.

[0035] The mesoporous silica catalyst is a metathesis catalyst which facilitates isomerization of 2-butene to 1-butene followed by cross-metathesis of the 2-butene and 1-butene into a metathesis product stream comprising propylene, and other alkenes/alkanes such as pentene. The MFI structured silica catalyst, which is downstream of the metathesis catalyst, is a cracking catalyst which produces propylene from C₄ or C₅ olefins in the metathesis product stream, and may also yield ethylene.

[0036] It is contemplated that the metathesis catalyst and the cracking catalyst are disposed in one reactor or multiple reactors. For example, it may be desirable to use separate reactors for the metathesis and cracking catalysts when they operate at different environmental conditions, including temperature and pressure. Regardless of whether one or multiple reactors contain the dual catalysts, the dual catalyst system will have a metathesis

catalyst zone or section and a downstream cracking catalyst zone or section. For example, the mesoporous silica metathesis catalyst may be located in the top part of the reactor and the MFI structured silica cracking catalyst may be disposed in the bottom part of the reactor, assuming the reactant stream enters the top portion of the reactor. For example, each catalyst may be positioned as discrete catalyst beds. Moreover, it is contemplated that the two catalysts of the dual catalyst system may be in contact with one another or separated. However, if the metathesis catalyst and cracking catalyst are in contact, it is desirable that the metathesis catalyst is still disposed upstream of the cracking catalyst. The catalysts can be used in the same reactor or with different reactors arranged in series. Alternatively, it is contemplated that the metathesis catalyst (mesoporous silica catalyst) is disposed in a first reactor and the cracking catalyst (MFI structured silica catalyst) is disposed in a separate second reactor downstream of the first reactor. In specific embodiments, there is a direct conduit between the first reactor and second reactor, so that the cracking catalyst can directly crack the product of the butene metathesis reaction. Various systems which incorporate the catalyst system are contemplated. For details regarding such systems, co-pending Saudi Aramco U.S. Application No 62/188,052 entitled *Systems and Methods of Producing Propylene* is incorporated by reference in its entirety.

[0037] Various methods of making the catalysts used in the dual catalyst system are contemplated. Specifically, the processes of wet impregnation and hydrothermal synthesis may be utilized; however, other catalyst synthesis techniques are also contemplated.

[0038] Various operating conditions are contemplated for the contacting of the butene stream with the dual catalyst system. For example, the butene stream may contact the dual catalyst system at a space hour velocity of about 10 to about 10,000 h⁻¹, or about 300 to about 1200 h⁻¹. Moreover, the butene stream may contact the catalyst system at a temperature of from about 200 to about 600 °C, or about 300 to about 600 °C. Furthermore, the butene stream may contact the catalyst system at a pressure from about 1 to about 30 bars, or about 1 to about 10 bars.

[0039] Optionally, the dual catalyst system may be pretreated prior to metathesis and/or cracking. For example, the dual catalyst system may be pretreated with N₂ for about 1 hour to

about 5 hours before metathesis at a temperature of at least about 400 °C, or at least about 500 °C.

[0040] The product stream yielded by the dual catalyst system may have at least an 80 mol. % conversion of butene and a propylene yield in mol. % of at least 40%. In a further embodiment, the product stream may have at least an 85 mol. % conversion of butene and a propylene yield in mol. % of the at least 45%. Moreover, the product stream may have at least a 15 mol. % yield of ethylene, or at least a 20 mol. % yield of ethylene. In yet another embodiment, the product stream may have at least 45 mol. % yield of propylene, or at least about a 50 mol. % yield of propylene.

[0041] Moreover, the product stream may comprise less than 1 about wt% aromatics, or less than about 5 wt% of alkanes and aromatics. Without being bound by theory, in some embodiments it may be desirable that the aromatics and alkanes yield be low as it indicates coke formation, which may result in catalyst deactivation.

[0042] EXAMPLES

[0043] The following examples show the preparation of various catalysts which are used in a combination as in the present dual catalysts.

[0044] *Example 1: Preparation of W-SBA-15(30)*

[0045] Sodium tungstate was used as the source of tungsten ion for the synthesis of W-SBA-15 by direct hydrothermal method. In a typical synthesis of W-SBA-15, tungsten was incorporated into the framework of mesoporous support SBA-15 depending upon the Si/W molar ratio. Pluronic® 123 (P123) was dissolved in HCl and tetraethylorthosilicate (TEOS) was added with vigorous stirring. Then, a calculated amount of sodium tungstate solution was added to the solution and stirred at 95 °C for 3 days under hydrothermal conditions. The resultant solid was filtered, dried and calcined at 550 °C for 5 hours. The catalysts obtained in this way were identified as W-SBA-15(30), where 30 represents the molar ratio of silicon to tungsten (Si/W). The molar ratio of the gel composition is 1 SiO₂: 0.3-0.6 WO₃: 0.0167 P123: 5.82 HCl: 190 H₂O.

[0046] *Example 2: Preparation of Silicalite-1*

[0047] In a typical synthesis, 4.26 grams (g) tetrapropylammonium bromide (TPA) and 0.7407 g ammonium fluoride was dissolved in 72 ml of water and stirred well for 15 minutes. Then, 12 g fumed silica was added and stirred well until homogenized. The obtained gel was autoclaved and kept at 200 °C for 2 days. The molar composition of gel was 1 SiO₂: 0.08 (TPA)Br: 0.10 NH₄F: 20 H₂O. The solid products obtained were washed with water and dried at 80 °C overnight. The template was removed by calcination in air at 750 °C for 5 hours.

[0048] *Example 3: Preparation of MFI-2000*

[0049] In a typical synthesis, 4.26 g TPA and 0.7407 g ammonium fluoride was dissolved in 72 ml of water and stirred well for 15 minutes. 12 g fumed silica was added and stirred well until homogenized. An appropriate amount of aluminum sulfate was added and the obtained gel was autoclaved and kept at 200 °C for 2 days. The molar composition of gel was 1 SiO₂: 0.0005 Al₂O₃: 0.08 (TPA)Br: 0.10 NH₄F: 20 H₂O. The solid products obtained were washed with water and dried at 80 °C overnight. The template was removed by calcination in air at 550 °C for 5 hours.

[0050] *Example 4: Preparation of 10WO₃/Q10*

[0051] 10WO₃/ CARiACT Q10 was prepared by the wet impregnation method. An aqueous solution of ammonium metatungstate [(NH₄)₆H₂W₁₂O₄₀•xH₂O] and the commercial silica support were mixed together and dried in an oven at 110 °C for 12 hours and calcined at 550 °C for 8 hours. As shown in Table 1 as follows, the supported tungsten oxide catalyst (10WO₃/Q10) has a lower surface area when compared to the parent Q10 material, indicating the presence of tungsten oxide on the support.

[0052] The SEM images of CARiACT Q10 support and 10WO₃/Q10 catalyst are shown in FIGS. 1 and 2, respectively. Both the CARiACT Q10 support and the tungsten loaded 10WO₃/Q10 have a particle size in the range of 75-125 nm. Lack of agglomeration of tungsten oxide particles in 10WO₃/Q10 indicates a high dispersion of tungsten oxide on the support. Referring to FIG. 2, the SEM image of MFI-2000 shows a uniform particle size

distribution with crystal size of about 35-50 μm . The X, Y, and Z axis of crystal are 50 μm , 16 μm , and 3 μm , respectively.

[0053] The XRD patterns of Q10, 10WO₃/Q10 and the MFI-2000 materials are shown in FIGS. 3-5. Referring to FIG. 4, the Q10 support shows a broad peak at 15-20° indicating the presence of amorphous silica in the material. Further referring to FIG. 4, the 10WO₃/Q10 catalyst shows peaks at 23.09, 23.57, 24.33 and 34.01 corresponding to the crystalline phase of WO₃. This shows the presence of WO₃ species in the catalyst. As shown in FIG. 5, the XRD patterns of MFI-2000 exhibit peaks characteristic of the MFI structure in the ranges 8-9° and 22-25°. The intensity of the peak at $2\theta = 8.8^\circ$ is comparable with the peaks in the range 22-25° indicating the formation of zeolite crystals along the b-axis.

Example 5: Catalyst Properties

[0054] Table 1 includes mechanical properties of the catalysts prepared in Examples 1-4, plus MFI 280 which is prepared similarly to MFI-2000 as disclosed in Example 3.

[0055] Table 1

Catalysts/Supports	BET Surface Area (m ² /g)	Pore Volume (cm ³ /g)	Pore Size Distribution (nm)	Total acidity (mmol/g)
Metathesis Catalysts/Supports				
W-SBA-15 (Si/W=30)	501	0.78	6.9	0.46
CARiACT Q10	300	1.00	100	
10WO ₃ /Q10	279	1.22	17.5	0.09
Cracking Catalysts				
MFI-280	400	0.23	2.0	0.07
MFI-2000	367	0.19	2.0	0.01
Silicalite-1	348	0.23	2.0	Not detected

[0056] *Example 6: Catalyst Performance of W-SBA-15 with Cracking Catalysts*

[0057] The prepared catalysts from Examples 1-4 were tested for their activity and selectivity to butene metathesis reaction in a fixed bed continuous flow reactor (ID 0.25 in, Autoclave Engineers Ltd.) at atmospheric pressure. A fixed amount of catalyst samples, 1 ml

of each catalyst type (with a total of 2 ml) was packed in the reactor tube with silicon carbide on top and bottom of the reactor. The catalysts were pretreated under N₂ at 550 °C for 1 hour. All reactions were carried out at a temperature of 550 °C, a GHSV (gas hourly space velocity) of 900 h⁻¹, and atmospheric pressure using 2-butene (5 milliliters/minutes (ml/min)) as feed with nitrogen as diluent (25 ml/min). The quantitative analysis of the reaction products were carried out on-line using Varian gas chromatograph with flame ionization detector (FID) (Varian 450-GC), equipped with GasPro porous layer open tubular column.

[0058] Table 2 indicates the catalytic performances of cracking catalysts MFI-280 and MFI-2000 individually and in a combination (dual) mode with catalyst W-SBA-15(30) in the metathesis and cracking reaction of 2-butene (Reaction temperature: 550° C, atmospheric pressure, GHSV of 900 h⁻¹). It can be seen that the combination of W-SBA-15 metathesis catalyst with downstream MFI-2000 cracking catalyst offered the highest yields of propylene.

[0059] Table 2

Product Component	MFI-280	W-SBA-15(30) MFI-280	MFI-2000	W-SBA-15(30) MFI-2000
Conversion 2-C ₄ (%)	95.67	94.16	93.72	91.00
Yield (mol %)				
C ₂ =	30.53	29.61	30.29	22.99
C ₃ =	29.14	33.19	38.98	45.46
1-C ₄ =	1.82	2.50	2.91	4.21
Isobutylene	3.92	5.72	5.96	8.52
C ₅ =	1.81	2.88	2.31	3.98
C ₆ =	0.00	0.00	0.00	0.32

[0060] Table 3 shows the catalytic performance of individual catalyst W-SBA-15(30) and a dual W-SBA-15(30)/silicalite-1 catalyst in the metathesis and cracking reaction of 2-butene (Reaction temperature: 550° C, atmospheric pressure, GHSV of 900 hr⁻¹).

[0061] Table 3

Product Component	W-SBA-15(30)	W-SBA-15(30) & Silicalite-1
Conversion 2-C ₄ (%)	81.69	87.03
Yield (mol %)		
C ₂ =	11.48	14.87
C ₃ =	35.54	43.58
1-C ₄ =	8.06	5.80
Isobutylene	3.24	11.28
C ₅ =	15.05	8.09
C ₆ =	4.20	0.38

Example 7: Catalyst Performance of CARiACT Q10 with Cracking Catalysts

[0062] The catalyst performance was also evaluated for the CARiACT Q10 metathesis catalyst as described in Example 4. The catalytic reaction of 2-butene (1:1 mixture of trans-2-butene & cis-2-butene) was performed in a fixed-bed tubular reactor (grade 316 stainless steel tube with an ID of 0.312 inches, OD of 0.562 inches and a length of 8 inches). In the experiment, the reactor is charged with 2 ml of the catalyst (single-bed) previously sieved to a particle size of 0.5-1.0 mm diameter. The catalyst sample was first activated in a nitrogen stream at 550 °C for 1 hours. The flow rates of feed (2-Butene) and N₂ were maintained at 5.0 ml/min and 25 ml/min, respectively, during the reaction. The reaction was carried out at a temperature of 550 °C at atmospheric pressure with a GHSV (gas hourly space velocity) of 900 h⁻¹ and a 5 hour time-on-stream (TOS). In the case of the dual catalyst system, 1 ml of each catalyst separated with glass wool was used.

[0063] The supported tungsten oxide catalyst was tested in both the single and dual catalyst systems and the results are shown in Table 4. The highest propylene selectivity is obtained for a dual catalyst system with 10WO₃/Q10 at the top (T) and MFI-2000 at the bottom (B) of the reactor. When 10WO₃/Q10 metathesis catalyst is used in a single-bed catalyst system, a propylene (C₃=) yield of 31.97 mol. % and a pentene (C₅=) yield of 12.70 mol. % are obtained. These results indicate that the pentenes formed during metathesis of butenes are not completely cracked into propylene and ethylene. However, the

10WO₃/Q10(T) /MFI-2000 (B) yielded 3.37 mol.% of pentene thus indicating that most of the pentenes formed during the metathesis reaction are cracked into propylene and ethylene. Thus, there is a clear advantage of using a dual catalyst system with the cracking catalyst at the bottom of the catalyst bed. Moreover, when comparing the 10WO₃/Q10(T) /MFI-2000(B) with the reverse arrangement of cracking catalyst upstream of metathesis catalyst, the 10WO₃/Q10(T)/MFI-2000 (B) yields approximately a 4.5 mol.% increase in propylene over the MFI-2000(T)/10WO₃/Q10(B) while only yielding slightly less (~1.5 mol.%) ethylene (C₂=). Thus, propylene yield is clearly maximized by using a dual catalyst system with the cracking catalyst at the bottom of the catalyst bed.

Table 4

Product Component	MFI-2000	10WO₃/Q10	10WO₃/Q10(T) MFI-2000 (B)	10WO₃/Q10 mixed MFI-2000	MFI-2000 (T) 10WO₃/Q10 (B)
Conversion 2-C ₄ = (%)	92.24	70.96	86.35	87.01	86.2
Yield (mol %)					
C ₂ =	29.39	7.95	23.01	24.76	24.85
C ₃ =	37.56	31.97	45.64	43.77	41.09
1-C ₄ =	2.80	10.83	4.78	4.87	4.98
Isobutylene	5.72	2.20	9.83	10.01	11.04
C ₅ =	2.25	12.70	3.37	3.52	3.59
C ₆ =	0.00	2.17	0.00	0.00	0.00

[0064] CALCULATION METHODOLOGIES

[0065] The surface area of the samples was measured by nitrogen adsorption at 77 K using AUTOSORB-1 (Quanta Chrome). Before adsorption measurements, samples (ca. 0.1 g) were heated at 220 °C for 2 hours under nitrogen flow. The nitrogen adsorption isotherms of catalysts were measured at liquid nitrogen temperature (77 K). The surface areas and pore size distributions were calculated by the Brunauer Emmett-Teller (BET) method and the Barrett-Joyner-Halenda (BJH) method, respectively. The total pore volume was estimated from the amount of N₂ adsorbed at P/P₀ = 0.99. Barret EP, Joyner LJ, Halenda PH, J. Am. Chem. Soc. 73 (1951) 373-380.

[0066] The zeolite samples were characterized by XRD with a Rigaku Mini-flex II system using nickel filtered CuK α radiation ($\lambda = 1.5406 \text{ \AA}$, 30 kV and 15 mA). The XRD patterns were recorded in static scanning mode from $1.2 - 50^\circ$ (2θ) at a detector angular speed of 2° min^{-1} with a step size of 0.02° .

[0067] SEM images were measured with a JEOL JSM-5800 scanning microscope at a magnification of 7000. Before taking SEM photographs, the samples were loaded on a sample holder, held with conductive aluminum tape, and coated with a film of gold in a vacuum with a Cressington sputter ion-coater for 20 seconds with 15 milliAmpere (mA) current.

[0068] It should now be understood that various aspects of the systems and methods of making propylene with the dual catalysts are described and such aspects may be utilized in conjunction with various other aspects.

[0069] In a first aspect, the disclosure provides a process for production of propylene comprising providing a dual catalyst system comprising a mesoporous silica catalyst impregnated with metal oxide, and a mordenite framework inverted (MFI) structured silica catalyst downstream of the mesoporous silica catalyst. The mesoporous silica catalyst includes a pore size distribution of about 2.5 nm to about 40 nm and a total pore volume of at least about $0.600 \text{ cm}^3/\text{g}$. The MFI structured silica catalyst includes total acidity of 0.001 mmol/g to 0.1 mmol/g. The process also comprises producing propylene from a stream comprising butene via metathesis and cracking by contacting the stream comprising butene with the dual catalyst system, where the stream comprising butene contacts the mesoporous silica catalyst before contacting the MFI structured silica catalyst.

[0070] In a second aspect, the disclosure provides a process of the first aspect, in which the mesoporous silica catalyst support is produced via wet impregnation or hydrothermal synthesis.

[0071] In a third aspect, the disclosure provides a process of either the first or second aspects, in which the butene stream comprises 2-butene, and optionally one or more of 1-butene, trans-2-butene, and cis-2-butene.

[0072] In a fourth aspect, the disclosure provides a process of any one of the first through third aspects, in which the mesoporous silica catalyst catalyzes isomerization of 2-butene to 1-butene followed by cross-metathesis of 2-butene and 1-butene into a metathesis product stream comprising propylene, and the MFI structured silica catalyst is a cracking catalyst which produces propylene from C₄ and C₅ olefins in the metathesis product stream.

[0073] In a fifth aspect, the disclosure provides a process of any one of the first through fourth aspects, in which the metal oxide of the mesoporous silica catalyst comprises one or more oxides of molybdenum, rhenium, tungsten, or combinations thereof.

[0074] In a sixth aspect, the disclosure provides a process of any one of the first through fifth aspects, in which the metal oxide of the mesoporous silica catalyst is tungsten oxide (WO₃).

[0075] In a seventh aspect, the disclosure provides a process of any one of the first through sixth aspects, in which the mesoporous silica catalyst has a molar ratio for silica/tungsten oxide of about 5 to about 60.

[0076] In an eighth aspect, the disclosure provides a process of any one of the first through seventh aspects, in which the mesoporous silica catalyst includes a pore size distribution of from about 2.5 nm to 20 nm.

[0077] In a ninth aspect, the disclosure provides a process of any one of the first through eighth aspects, in which the mesoporous silica catalyst has a surface area of about 250 m²/g to about 600 m²/g.

[0078] In a tenth aspect, the disclosure provides a process of any one of the first through ninth aspects, in which the MFI structured silica catalyst is free of acidity modifiers selected from the group consisting of rare earth modifiers, phosphorus modifiers, potassium modifiers, and combinations thereof.

[0079] In an eleventh aspect, the disclosure provides a process of any one of the first through tenth aspects, in which the mesoporous silica catalyst has a particle size of about 20 nm to about 200 nm.

[0080] In a twelfth aspect, the disclosure provides a process of any one of the first through eleventh aspects, in which the mesoporous silica catalyst has an individual crystal size ranging from about 10 to about 40 μm .

[0081] In a thirteenth aspect, the disclosure provides a process of any one of the first through twelfth aspects, in which the MFI structured silica catalyst is alumina free.

[0082] In a fourteenth aspect, the disclosure provides a process of any one of the first through thirteenth aspects, in which the MFI structured silica catalyst is alumina free or alumina containing.

[0083] In a fifteenth aspect, the disclosure provides a process of any one of the first through fourteenth aspects, in which the MFI structured silica catalyst has a molar ratio of silica to alumina of about 200 to about 3000.

[0084] In a sixteenth aspect, the disclosure provides a process of any one of the first through fifteenth aspects, in which the MFI structured silica catalyst has a molar ratio of silica to alumina of about 200 to about 3000.

[0085] In a seventeenth aspect, the disclosure provides a process of any one of the first through sixteenth aspects, in which the MFI structured silica catalyst has a surface area of at about 300 m^2/g to about 425 m^2/g .

[0086] In an eighteenth aspect, the disclosure provides a process of any one of the first through seventeenth aspects, in which the MFI structured silica catalyst has a pore size distribution of from about 1.5 nm to 3 nm and a pore volume of at about 0.1 cm^3/g to about 0.3 cm^3/g .

[0087] In a nineteenth aspect, the disclosure provides a process of any one of the first through eighteenth aspects, in which the MFI structured silica catalyst has a crystal size of about 10 μm to about 40 μm .

[0088] In a twentieth aspect, the disclosure provides a process of any one of the first through twentieth aspects, in which the contact between the butene and the catalyst occurs at a space hour velocity of about 300 to about 1200 h^{-1} .

[0089] In a twenty-first aspect, the disclosure provides a process of any one of the first through twentieth aspects, in which the contact between the butene and the catalyst is at a temperature of about 300 to about 600 °C.

[0090] In a twenty-second aspect, the disclosure provides a process of any one of the first through twenty-first aspects, in which the contact between the butene and the catalyst is at a pressure of about 1 to about 10 bars.

[0091] In a twenty-third aspect, the disclosure provides a process of any one of the first through twenty-second aspects, in which the process achieves at least an 85 mol. % conversion of butene and a propylene yield in mol. % of the at least 45%.

[0092] In a twenty-fourth aspect, the disclosure provides a process of any one of the first through twenty-third aspects, in which the process achieves at least an 85 mol. % conversion of butene and a propylene yield in mol. % of at least 45%.

[0093] In a twenty-fifth aspect, the disclosure provides a process of any one of the first through twenty-fourth aspects, in which the process achieves a yield of at least a 15 mol. % ethylene.

[0094] In a twenty-sixth aspect, the disclosure provides a process of any one of the first through twenty-fifth aspects, in which the process achieves a yield of at least 20 mol.% ethylene and a propylene yield in mol. % of the at least 45%.

[0095] In a twenty-seventh aspect, the disclosure provides a dual catalyst system for producing propylene from butene, which may be utilized in the process of process of any one of the first through twenty-sixth aspects, where the dual catalyst system comprising a metathesis catalyst zone and a cracking catalyst zone downstream of the metathesis catalyst zone. The metathesis catalyst zone comprises mesoporous silica catalyst impregnated with metal oxide, where the mesoporous silica catalyst includes a pore size distribution of at least about 2.5 nm to about 40 nm and a total pore volume of at least about 0.600 cm³/g. The cracking catalyst zone comprises a mordenite framework inverted (MFI) structured silica catalyst, where the MFI structured silica catalyst includes a pore size distribution of at least 1.5 nm to 3 nm, and a total acidity of 0.001 mmol/g to 0.1 mmol/g.

[0096] In a twenty-eighth aspect, the disclosure provides a dual catalyst system of the twenty-seventh aspect, in which the metathesis catalyst zone and the cracking catalyst zone are disposed in one reactor.

[0097] In a twenty-ninth aspect, the disclosure provides a dual catalyst system of any one of the twenty-seventh or twenty-eighth aspects, in which the metathesis catalyst zone is disposed in a first reactor and the cracking catalyst zone is disposed in a second reactor downstream of the first reactor.

[0098] In a thirtieth aspect, the disclosure provides a dual catalyst system of the thirtieth aspect, in which there is a conduit between the first reactor and the second reactor.

[0099] In a thirty-first aspect, the disclosure provides a dual catalyst system of any one of the twenty-seventh through thirtieth aspects, in which the mesoporous silica catalyst has a molar ratio for silica/metal oxide of about 10 to about 50.

[00100] In a thirty-second aspect, the disclosure provides a dual catalyst system of any one of the twenty-seventh through thirty-first aspects, in which the metal oxide of the mesoporous silica catalyst is tungsten oxide (WO_3).

[00101] In a thirty-third aspect, the disclosure provides a dual catalyst system of any one of the twenty-seventh through thirty-second aspects, in which the MFI structured silica catalyst is alumina free or comprises alumina.

[00102] In a thirty-fourth aspect, the disclosure provides a dual catalyst system of any one of the twenty-seventh through thirty-third aspects, in which the MFI structured silica catalyst has a molar ratio of silica to alumina of about 200 to about 3000.

[00103] In a thirty-fifth aspect, the disclosure provides a dual catalyst system of any one of the twenty-seventh through thirty-fourth aspects, in which the MFI structured silica catalyst is free of acidity modifiers selected from the group consisting of rare earth modifiers, phosphorus modifiers, potassium modifiers, and combinations thereof.

[00104] It should be apparent to those skilled in the art that various modifications and variations can be made to the described embodiments without departing from the spirit and

scope of the claimed subject matter. Thus it is intended that the specification cover the modifications and variations of the various described embodiments provided such modification and variations come within the scope of the appended claims and their equivalents.

CLAIMS

1. A dual catalyst system for producing propylene from butene, the dual catalyst system comprising a metathesis catalyst zone and a cracking catalyst zone downstream of the metathesis catalyst zone where:
- the metathesis catalyst zone comprises mesoporous silica catalyst impregnated with metal oxide, where the mesoporous silica catalyst includes a pore size distribution of at least 2.5 nm to 40 nm and a total pore volume of at least 0.600 cm³/g; and
- the cracking catalyst zone comprises a mordenite framework inverted (MFI) structured silica catalyst, where the MFI structured silica catalyst includes a pore size distribution of at least 1.5 nm to 3 nm, and a total acidity of 0.001 mmol/g to 0.1 mmol/g.
2. The dual catalyst system of claim 1 where the metathesis catalyst zone and the cracking catalyst zone are disposed in one reactor.
3. The dual catalyst system of claim 1 where the metathesis catalyst zone is disposed in a first reactor and the cracking catalyst zone is disposed in a second reactor downstream of the first reactor.
4. The dual catalyst system of claim 3 further comprising a conduit between the first reactor and the second reactor.
5. The dual catalyst system of claim 1 where the metal oxide of the mesoporous silica catalyst comprises one or more oxides of molybdenum, rhenium, tungsten, or combinations thereof.
6. The dual catalyst system of claim 1 where the mesoporous silica catalyst has a molar ratio for silica/metal oxide of 10 to 50.

7. The dual catalyst system of claim 1 where the metal oxide of the mesoporous silica catalyst is tungsten oxide (WO_3).

5 8. The dual catalyst system of claim 1 where the MFI structured silica catalyst is alumina free.

9. The dual catalyst system of claim 1 where the MFI structured silica catalyst comprises alumina.

10 10. The dual catalyst system of claim 9 where the MFI structured silica catalyst has a molar ratio of silica to alumina of 200 to 3000.

11. The dual catalyst system of claim 1 where the MFI structured silica catalyst is free of acidity modifiers selected from the group consisting of rare earth
15 modifiers, phosphorus modifiers, potassium modifiers, and combinations thereof.