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(57) Abstract: A heterogeneous catalyst that is a combination of rhodium, zinc, iron, a fourth metal and at least one metal selected from alkali metals and alkaline earth metals on a catalyst support (e.g. at least one of silica, alumina, titania, magnesia, zinc aluminate (ZnAl₂O₄), magnesium aluminate (MgAl₂O₄), magnesia-modified alumina, zinc oxide-modified alumina, zirconium oxide-modified alumina, and zinc oxide) and use of the catalyst in converting an alkylene to an oxygenate that has one more carbon atom than the alkylene.



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HETEROGENEOUS CATALYST AND ITS USE

This application is a non-provisional application claiming priority from the U.S. Provisional Patent Application No. 61/441,679, filed on February 11, 2011, entitled "HETEROGENEOUS CATALYST AND ITS USE" the teachings of which are

5 incorporated by reference herein, as if reproduced in full hereinbelow.

This invention relates to a heterogeneous catalyst that comprises a promoted combination of rhodium (Rh), zinc (Zn), iron (Fe) and at least one additional metal selected from a group consisting of gold (Au), cerium (Ce), cobalt (Co), copper (Cu), lanthanum (La), chromium (Cr), manganese (Mn), niobium (Nb), an alkali metal and an alkaline earth
10 metal on a catalyst support and to use of such heterogeneous catalyst in converting a feedstream of an alkylene (e.g. ethylene) and synthesis gas ("syngas", a mixture of carbon monoxide (CO) and hydrogen (H₂)) to a product stream that comprises an oxygenate that has one carbon atom more than the alkylene in the feedstream (i.e. at least one three carbon (C₃) oxygenate (e.g. propionaldehyde or propanol) when the alkylene is ethylene).

15 United States Patent (US) 4,361,711 (Blaskie et al.) discloses a single step process to catalytically convert a mixture of an olefin (18 carbon atoms (C₁₈) or less), CO and H₂ to alcohols using a Rh catalyst. The catalyst, represented by formula A_aRhO_x, is a Rh-containing oxide complex that comprises at least one additional element (A) selected from Fe, Zn, iridium (Ir), ruthenium (Ru), Nb, Cr, Mn and platinum (Pt). In the formula, a
20 is 0.001 to 10 and x is greater than 0, but less than a number sufficient to satisfy the valence requirements of the other elements present when in a fully oxidized state. For preferred catalysts A is Zn, Fe and/or Mn and a is 0.6 to 2.0. The oxide complexes, when in use, are in a reduced state such that they contain less oxygen than necessary to satisfy all of the valence requirements of the metals present in a fully oxidized state. The oxide complexes
25 may be used neat, but are preferably disposed on a conventional catalyst support material such as silica, alumina, zirconia, kieselguhr, titania and molecular sieves.

W. M. H. Sachtler et al., in "Catalytic Site Requirements for Elementary Steps in Syngas Conversion to Oxygenates over Promoted Rhodium", Journal of Physical Chemistry, volume 90 (1986), pages 4752-4758, presents information on effects of various
30 promoter metals that modify performance of a Rh-containing catalyst in synthesis (syngas) conversion. The promoter metals include Mn, zirconium (Zr), titanium (Ti), vanadium (V) and Nb. Catalyst supports include oxides of Zn, magnesium (Mg), calcium (Ca), La, neodymium (Nd), Zr, Ti, Nb, Mn, silicon (Si) and aluminum (Al).

US 4,492,773 (Ball et al.) teaches production of one to four carbon (C₁ to C₄) oxygenates by contacting syngas at a temperature within a range of 150 degrees Celsius (°C) to 450 °C and a pressure within a range of from 1 bar (100 kilopascals (KPa) to 700 bars (70,000 KPa) with a catalyst comprising a supported mixture of a Rh component and a silver (Ag) component. Other metal components that may be incorporated include Fe, Mn, molybdenum (Mo), tungsten (W), Ru, Cr, thorium (Th) and Zr. Support materials include silica, alumina, silica/alumina, magnesia, thoria, titania, chromia, zirconia, and active carbon, with silica (SiO₂) being preferred.

In some aspects, this invention is a heterogeneous catalyst consisting essentially of a combination of rhodium, zinc, iron, a fourth metal and at least one metal selected from alkali metals and alkaline earth metals on a catalyst support, the combination of metals being represented by general formula Rh_aZn_bFe_cX_dY_eO_f wherein X is at least one fourth metal selected from a group consisting of Au, Ce, Co, Cu, La, Cr, Mn and Nb, Y is at least one of an alkali metal and an alkaline earth metal, a is a real number within a range of from 0.1 millimole per hectogram (mmol/hg) to 50 mmol/hg, b is a real number within a range of from 0.1 mmol/hg to 75 mmol/hg, c is a real number within a range of from 0.1 mmol/hg to 100 mmol/hg, d is a real number within a range of from greater than or equal to 0 mmol/hg to 50 mmol/hg, e is a real number within a range of from greater than or equal to 0 mmol/hg to 1500 mmol/hg, and f is a real number needed to balance the total charges of Rh, Zn, Fe, X and Y elements, provided that provided that d and e cannot both be 0 and when d is greater than 0 and X is at least one of Cr, Mn and Nb, e is also greater than 0, the catalyst support being at least one of silica, alumina, titania, magnesia, zinc aluminate (ZnAl₂O₄), magnesium aluminate (MgAl₂O₄), magnesia-modified alumina, zinc oxide-modified alumina, zirconium oxide-modified alumina, and zinc oxide. In some aspects, at least one of the metals is in a partially reduced state such that f is greater than 0, but less than a number sufficient to satisfy the valence requirements of the other elements present when in a fully oxidized state.

In some aspects, the heterogeneous catalyst is admixed with an amount of an alkali metal carbonate or alkaline earth metal carbonate. The amount of alkali metal carbonate or alkaline earth metal carbonate, preferably alkali metal carbonate, is preferably within a range of from greater than 0.1 mmol/hg to 75 mmol/hg based upon combined weight of the heterogeneous catalyst and the alkali metal carbonate. The alkali metal carbonate is preferably selected from sodium carbonate and lithium carbonate.

In some aspects, this invention is a process of converting a feedstream comprising a mixture of CO, H₂ and alkylene (e.g. ethylene, propylene, butylene, pentene, hexene, heptene or octene) to a product stream that comprises at least one oxygenate that has one more carbon atom than the alkylene in the feedstream (e.g. a three carbon oxygenate when the alkylene is ethylene), which process comprises placing the feedstream in contact with the heterogeneous catalyst or the admixture of the heterogeneous catalyst and an alkali metal carbonate under conditions sufficient to effect conversion of the feedstream to the product stream, said conditions including a temperature within a range of from 100 °C TO 450 °C, a pressure within a range of from 12 pounds per square inch gauge (psig) (82.7 kilopascals (KPa)) to 4,000 psig (27.6 megapascals (MPa)), a gas hourly space velocity (GHSV) within a range of from 25 reciprocal hours (h⁻¹) to 25,000 h⁻¹, and a feedstream ratio of alkylene to CO to H₂ (C₂H₄:CO:H₂) within a range of from 0.01:10:10 to 10.0:0.01:0.01. The feedstream may also contain other components like methane, nitrogen, carbon dioxide, acetylene, hydrogen sulfide, sulfur dioxide, alkanes (e.g. ethane or propane). The feedstream may be a mixture of more than one alkylenes (e.g. ethylene and propylene).

The heterogeneous catalyst disclosed herein and represented by general formula Rh_aZn_bFe_cX_dY_eO_f consists essentially of a combination of Rh, Zn, Fe, a fourth metal (X) and at least one metal (Y) selected from alkali metals and alkaline earth metals on a catalyst support. X is at least one metal selected from a group consisting of Au, Ce, Co, Cu, La, Cr, Mn and Nb. Y is at least one of an alkali metal and an alkaline earth metal. In the formula, a is a real number within a range of from 0.1 mmol/hg to 50 mmol/hg, b is a real number within a range of from 0.1 mmol/hg to 75 mmol/hg, c is a real number within a range of from 0.1 mmol/hg to 100 mmol/hg, d is a real number within a range of from greater than or equal to 0 mmol/hg to 50 mmol/hg, e is a real number within a range of from greater than or equal to 0 mmol/hg to 1500 mmol/hg, and f is a real number needed to balance the total charges of Rh, Zn, Fe, X and Y elements. In the formula, d and e cannot both be 0 and e must be greater than 0 when X is at least one of Cr, Mn and Nb. The catalyst support is at least one of silica, alumina, titania, magnesia, zinc aluminate (ZnAl₂O₄), magnesium aluminate (MgAl₂O₄), magnesia-modified alumina, zinc oxide-modified alumina, zirconium oxide-modified alumina, and zinc oxide. Silica, magnesia, magnesium aluminate and alumina constitute preferred supports.

In the process of converting a feedstream comprising a mixture of CO, H₂ and alkylene to a product stream that comprises at least one oxygenate that has one carbon more than the alkylene in the feedstream, place the feedstream in contact with the heterogeneous catalyst or the admixture of the heterogeneous catalyst and an alkali metal carbonate or alkaline earth metal carbonate under conditions sufficient to effect conversion
5 of the feedstream to the product stream. The conditions include a temperature within a range of from 100 °C TO 450 °C, a pressure within a range of from 12 psig (82.7 KPa) to 4,000 psig (27.6 MPa), a gas hourly space velocity (GHSV) within a range of from 25 h⁻¹ to 25,000 h⁻¹, and a feedstream ratio of alkylene (C_nH_{2n}, where n is an integer within a range of
10 from 2 to 8) to CO to H₂ (C_nH_{2n}:CO:H₂) within a range of from 0.01:10:10 to 10.0:0.01:0.01.

The alkali metals include sodium (Na), lithium (Li), potassium (K), rubidium (Rb), cesium (Cs) and francium (Fr). The alkaline earth metals include magnesium (Mg), beryllium (Be), calcium (Ca), strontium (Sr), barium (Ba) and radium (Ra). When the
15 catalyst includes component Y, one may use at least alkali metal, or at least one alkaline earth metal or a combination of at least one alkali metal and at least one alkaline earth metal.

One may admix an alkali metal carbonate such as sodium carbonate with catalyst compositions represented by the above general formula. The alkali metal carbonate
20 appears to reduce catalyst acidity, a possible explanation for a reduced tendency to promote hydrogenation of alkenes to alkenes during the process of at least some aspects of this invention.

The process of at least some aspects of this invention has utility in producing at least one oxygenate (e.g. a C₃ oxygenate). The oxygenates, in turn have utility in serving
25 as feedstocks for production of other chemicals such as production of propylene by dehydration of the C₃ oxygenate propanol. Propylene, in turn, has utility as a feedstock in making a variety of polymeric materials such as polypropylene that finds a number of uses in fabricated articles.

The heterogeneous catalysts provide an ethylene conversion of more than 10
30 mole percent (mol%), based upon total moles of alkylene (e.g. ethylene) in the feedstream, and a selectivity to oxygenates (e.g. C₃ oxygenates when the alkylene is ethylene, preferably to propanol and propanal (propionaldehyde)) of at least 30 mol% based upon total moles of

product in the product stream. Selectivity to C₃ oxygenates preferably favors propanol over propanal such that the product stream contains more propanol than propanal.

Arabic numerals designate Examples (Ex) of the present invention and capital alphabetic letters indicate Comparative Examples (Comp Ex or CEx).

5 CEx A

In a 50 ml round bottom flask equipped with a stirring bar, add an aqueous solution containing 0.0128 gram (g) rhodium chloride trihydrate (RhCl₃·3H₂O) (Hindustan Platinum India Limited) and 0.0018 g sodium nitrate (NaNO₃) (S.D. Fine) dissolved in 12.5 milliliters (ml) of distilled water to 0.5 g of silica (Aerosil™ 300, Degussa, surface area= 10 300 ± 30 square meters per gram (m²/g)) with constant stirring at room temperature (nominally 25°C) for an hour. Subject container contents to drying first under vacuum at 80 °C for 1 hr and then at 120 °C for 4 hours (hrs). Calcine dried container contents in air at 400 °C for 4 hrs to yield a silica-supported Rh catalyst. The catalyst is represented as Rh₁Na_{0.1}/SiO₂ (Rh: 9.7 mmol/hg; Na: 4.3 mmol/hg)

15 Evaluate catalyst performance using a high pressure parallel fixed bed reactor (PFBR) (PFBR System P/N;132088 from Symyx™ Technologies Inc) , a modular reactor composed of three bays, each of which contains 16 reactor tubes. The tubes in each bay are enclosed in a stainless steel bell jar capable of being pressurized with nitrogen (N₂) at the same pressure as that used in each reaction. Load reactor tubes with 200 microliters 20 (μL) of catalyst, reduce the catalyst in situ at 35 bar (3.5 megapascals (MPa)) for three hours at 350°C (heating rate of 5°C per minute) using a gaseous mixture of 90 volume percent (vol%) hydrogen (H₂) and 10 vol% N₂, each vol% being based on total gaseous mixture volume. Cool the catalyst to 280°C

25 Test the catalyst at a pressure of 35 bar (3.5 MPa), temperatures of 280°C, 300°C and 320°C and GHSV of 6744 reciprocal hours (hr⁻¹) using a feed mixture of 42.6 vol% H₂, 42.6 vol% CO, 4.8 vol% ethylene and 10 vol% N₂, each vol% being based on total feed mixture volume. Continue testing at 320°C but at a pressure of 90 bar (9 MPa), then return the pressure to 35 bar (3.5 MPa) and test at 340°C. Evaluate reactor tube effluent 30 using a Siemens process GC. Replicate this catalyst test cycle two additional times and report test results as an average of three test cycles in Table 1 below.

CEx B

Replicate CEx A with changes. First, eliminate $\text{RhCl}_3 \cdot 3\text{H}_2\text{O}$. Second, add 0.0045 g of $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (S.D. Fine) and 0.0049 g of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (S.D. Fine). Third, use a mortar and pestle to physically mix such catalyst with 0.0025 g of sodium carbonate (Na_2CO_3 also referred to herein as "NC") to yield a catalyst sample suitable for testing. The catalyst is represented as $\text{Zn}_{0.2}\text{Co}_{0.2}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{SiO}_2$. (Zn: 3.1 mmol/hg; Co: 3.4 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 1

Replicate CEx B but add 0.0128 g $\text{RhCl}_3 \cdot 3\text{H}_2\text{O}$ (Hindustan Platinum India Limited), and substitute 0.0052 g of $\text{Fe}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (S.D. Fine) for $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{SiO}_2$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 2

Replicate Ex 1, but add 0.0017g of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ (Acros). The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Au}_{0.2}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{SiO}_2$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Au: 1.0 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 3

Replicate Ex 1, but add 0.0012 g of cerium nitrate ($\text{Ce}(\text{NO}_3)_3$) (S. D. Fine). The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Ce}_{0.1}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{SiO}_2$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Ce: 0.7 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 4

Replicate Ex 3, but substitute 0.0049 g of cobalt nitrate hexahydrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) (S. D. Fine) for the cerium nitrate. The catalyst is represented as $\text{Rh}_1\text{-Zn}_{0.2}\text{Fe}_{0.2}\text{Co}_{0.2}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{SiO}_2$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Co: 3.4 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 5

Replicate Ex 4, but substitute 0.0038 g of copper nitrate hexahydrate ($\text{Cu}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) (S. D. Fine) for the $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. The catalyst is represented as $\text{Rh}_1\text{-Zn}_{0.2}\text{Fe}_{0.2}\text{Cu}_{0.2}\text{Na}_{0.1}\text{NC}_{0.5}/\text{SiO}_2$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cu: 3.1 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 6

Replicate Ex 5, but substitute 0.0049 g of lanthanum nitrate trihydrate ($\text{La}(\text{NO}_3)_3 \cdot 3\text{H}_2\text{O}$) (S. D. Fine) for the $\text{Cu}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. The catalyst is represented as

Rh₁Zn_{0.2}Fe_{0.2}La_{0.2}Na_{0.1}-NC_{0.5}/SiO₂. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; La: 1.4 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 7

Replicate Ex 5, but substitute 0.0025 g of niobium oxalate hexahydrate
5 (Nb₂(C₂O₄)₅·2NH₄C₂O₄·6H₂O (S. D. Fine) for the La(NO₃)₂·3H₂O. The catalyst is represented as Rh₁Zn_{0.2}Fe_{0.2}Nb_{0.1}Na_{0.1}-NC_{0.5}/SiO₂. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Nb: 1.1 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 8

Replicate Ex 4, but eliminate NaNO₃ and Na₂CO₃. The catalyst is
10 represented as Rh₁Zn_{0.2}Fe_{0.2}Co_{0.2}/SiO₂. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Co: 3.4 mmol/hg).

Ex 9

Replicate Ex 8, substitute 0.5 g MgO for SiO₂. The catalyst is represented as
15 Rh₁Zn_{0.2}Fe_{0.2}Co_{0.2}/MgO. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Co: 3.4 mmol/hg).

Ex 10

Replicate Ex 1, but add 0.0157 g of Cr(NO₃)₃·9H₂O, and substitute 0.5 g
MgO for SiO₂. The catalyst is represented as Rh₁Zn_{0.2}Fe_{0.2}Cr_{0.5}Na_{0.1}-NC_{0.5}/MgO. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).
20

Ex 11

Replicate Ex 10, but substitute 0.5 g MgAl₂O₄ for MgO. The catalyst is
represented as Rh₁Zn_{0.2}Fe_{0.2}Cr_{0.5}Na_{0.1}-NC_{0.5}/MgAl₂O₄. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

25 Ex 12

Replicate Ex 10, but substitute 0.5 g MgO-Al₂O₃ for MgO. The catalyst is
represented as Rh₁Zn_{0.2}Fe_{0.2}Cr_{0.5}Na_{0.1}-NC_{0.5}/MgO-Al₂O₃. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 13

30 Replicate Ex 10, but substitute 0.5 g TiO₂ for MgO. The catalyst is represented as Rh₁Zn_{0.2}Fe_{0.2}Cr_{0.5}Na_{0.1}-NC_{0.5}/TiO₂. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 14

Replicate Ex 10, but substitute 0.5 g ZnAl_2O_4 for MgO. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Cr}_{0.5}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{ZnAl}_2\text{O}_4$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

5 Ex 15

Replicate Ex 10, but substitute 0.5 g ZnO for MgO. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Cr}_{0.5}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{ZnO}$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 16

10 Replicate Ex 10, but substitute 0.5 g $\text{ZnO-Al}_2\text{O}_3$ for MgO. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Cr}_{0.5}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{ZnO-Al}_2\text{O}_3$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 17

15 Replicate Ex 10, but substitute 0.5 g $\text{ZrO}_2\text{-Al}_2\text{O}_3$ for MgO. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Cr}_{0.5}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{ZrO}_2\text{-Al}_2\text{O}_3$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 18

20 Replicate Ex 11, but add 0.0031 g $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Cr}_{0.5}\text{Mn}_{0.2}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{MgAl}_2\text{O}_4$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Cr: 9.6 mmol/hg; Mn: 3.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 19

25 Replicate Ex 10, but substitute 0.0031 g $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ for $\text{Cr}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Mn}_{0.2}\text{Na}_{0.1}\text{-NC}_{0.5}/\text{MgO}$. (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Mn: 3.6 mmol/hg; Na: 4.3 mmol/hg; NC: 4.7 mmol/hg).

Ex 20

30 Replicate Ex 9, but add 0.0031 g $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. The catalyst is represented as $\text{Rh}_1\text{Zn}_{0.2}\text{Fe}_{0.2}\text{Co}_{0.2}\text{Mg}_{0.5}/\text{MgO}$ (Rh: 9.7 mmol/hg; Zn: 3.1 mmol/hg; Fe: 3.6 mmol/hg; Co: 3.4 mmol/hg; Mg: 20.6 mmol/hg).

TABLE 1

Ex. No.	Temperature, °C	X(Ethylene), %	S(propanal+propanol), %
CEx A	280	11.70	57.60
CEx B	280	3.70	36.86
Ex 1	280	7.83	63.91
Ex 2	280	15.91	66.84
Ex 3	280	17.70	67.99
Ex 4	280	32.63	69.67
Ex 5	280	16.68	60.46
Ex 6	280	14.20	66.82
Ex 7	280	15.38	53.10
CEx A	300	11.80	57.20
CEx B	300	10.07	29.96
Ex 1	300	12.82	64.21
Ex 2	300	24.95	66.49
Ex 3	300	28.02	65.89
Ex 4	300	48.56	68.03
Ex 5	300	26.69	58.36
Ex 6	300	23.26	64.63
Ex 7	300	24.18	58.86
CEx A	320	15.00	54.10
CEx B	320	19.42	25.13
Ex 1	320	21.75	60.38
Ex 2	320	37.95	62.74
Ex 3	320	42.89	62.65
Ex 4	320	68.03	62.83
Ex 5	320	41.09	53.80
Ex 6	320	35.91	60.74
Ex 7	320	36.97	59.28
CEx A	340	14.30	51.90
CEx B	340	0.76	30.00
Ex 1	340	30.66	54.78
Ex 2	340	52.28	58.51
Ex 3	340	57.94	59.05
Ex 4	340	78.17	59.70
Ex 5	340	46.09	48.52
Ex 6	340	50.20	55.41
Ex 7	340	51.52	53.98

Note: 'X' refers to conversion, 'S' refers to selectivity

TABLE 2

Ex. No.	Temperature, °C	Pressure, (MPa)	X(Ethylene), %	S(propanal+propanol), %
Ex 8	280	3.5	15.44	60.95
Ex 8	300	3.5	28.63	60.00
Ex 8	320	3.5	45.54	52.56
Ex 8	340	3.5	71.77	48.18
Ex 8	280	9.0	27.83	72.49
Ex 8	300	9.0	46.85	69.69
Ex 8	340	9.0	88.74	56.97
Ex 9	280	3.5	47.09	58.13
Ex 9	300	3.5	47.02	56.65
Ex 9	320	3.5	63.72	50.52
Ex 9	340	3.5	81.95	40.90
Ex.10	280	3.5	48.37	67.18
Ex.10	300	3.5	50.06	67.31
Ex.10	320	3.5	67.50	61.81
Ex.10	340	3.5	41.88	68.28
Ex.10	320	9.0	65.31	71.58
Ex.10	340	9.0	71.91	68.87
Ex.11	280	3.5	73.06	59.28
Ex.11	300	3.5	81.87	54.31
Ex.11	320	3.5	92.98	44.50
Ex.11	340	3.5	78.78	34.72
Ex.11	320	9.0	96.24	47.76
Ex.11	340	9.0	92.33	38.70
Ex.12	280	3.5	50.51	55.80
Ex.12	300	3.5	71.16	47.62
Ex.12	320	3.5	87.98	35.72
Ex.12	340	3.5	95.60	19.98
Ex.12	320	9.0	95.94	33.07
Ex.12	340	9.0	99.73	16.93
Ex.13	280	3.5	77.96	16.17
Ex.13	300	3.5	96.39	9.80
Ex.13	320	3.5	99.39	5.95
Ex.13	340	3.5	93.39	5.92
Ex.13	340	9.0	99.49	6.66
Ex.14	280	3.5	52.63	62.80
Ex.14	300	3.5	73.87	55.70
Ex.14	320	3.5	92.42	41.70
Ex.14	340	3.5	98.03	18.02
Ex.14	320	9.0	98.38	37.73
Ex.14	340	9.0	99.80	18.59

TABLE 2 (continued)

Ex. No.	Temperature, °C	Pressure, (MPa)	X(Ethylene), %	S(propanal+propanol), %
Ex.15	280	3.5	3.49	21.05
Ex.15	300	3.5	6.00	16.04
Ex.15	320	3.5	10.91	9.84
Ex.15	340	3.5	20.24	4.40
Ex.15	320	9.0	31.06	20.24
Ex.15	340	9.0	46.19	13.82
Ex.16	280	3.5	63.66	59.84
Ex.16	300	3.5	64.99	53.97
Ex.16	320	3.5	90.23	44.13
Ex.16	340	3.5	60.50	36.19
Ex.16	320	9.0	68.06	45.97
Ex.16	340	9.0	87.45	38.96
Ex.17	280	3.5	3.84	56.84
Ex.17	300	3.5	4.51	49.67
Ex.17	320	3.5	9.29	42.86
Ex.17	340	3.5	9.17	32.34
Ex.17	320	9.0	14.45	42.97
Ex.17	340	9.0	21.15	35.63
Ex.18	280	3.5	81.19	61.38
Ex.18	300	3.5	89.30	55.10
Ex.18	320	3.5	98.04	45.03
Ex.18	340	3.5	87.08	34.52
Ex.18	320	9.0	95.95	46.41
Ex.18	340	9.0	96.46	38.40
Ex.19	280	3.5	29.27	64.24
Ex.19	300	3.5	35.37	60.27
Ex.19	320	3.5	45.09	55.34
Ex.19	340	3.5	35.05	58.28
Ex.19	320	9.0	48.88	67.29
Ex.19	340	9.0	56.85	64.34
Ex.20	280	3.5	78.89	61.06
Ex.20	300	3.5	82.67	59.88
Ex.20	320	3.5	95.29	54.43
Ex.20	340	3.5	98.81	42.51
Ex.20	280	9.0	66.31	67.86
Ex.20	300	9.0	89.70	63.79

Note: 'X' refers to conversion, 'S' refers to selectivity

5 As seen in Table 1, the present heterogeneous catalyst shown in Ex 1-20 and having a general formula $Rh_aZn_bFe_cX_dY_eO_f$ wherein X=Au, Ce, Co, Cu, La, Mn, Cr and/or Nb, Y=alkali and/or alkaline earth metal produces much better combined selectivity to

propanal and propanol and/or higher ethylene conversion compared to the Rh-Alkali (CEx A) or Rh-Zn-Fe-Alkali (CEx B) compositions without other metal promoters.

WHAT IS CLAIMED IS:

1. A heterogeneous catalyst consisting essentially of a combination of rhodium, zinc, iron, a fourth metal and at least one metal selected from alkali metals and alkaline earth metals on a catalyst support, the combination of metals represented by general
5 formula $Rh_aZn_bFe_cX_dY_eO_f$ wherein X is at least one fourth metal selected from a group consisting of gold, cerium, cobalt, copper, lanthanum, chromium, manganese and niobium, Y is at least one of an alkali metal and an alkaline earth metal, a is a real number within a range of from 0.1 mmol/hg to 50 mmol/hg, b is a real number within a range of from 0.1 mmol/hg to 75 mmol/hg, c is a real number within a range of from 0.1 mmol/hg to 100
10 mmol/hg, d is a real number within a range of from greater than or equal to 0 mmol/hg to 50 mmol/hg, e is a real number within a range of from greater than or equal to 0 mmol/hg to 1500 mmol/hg, and f is a real number needed to balance the total charges of Rh, Zn, Fe, X and Y elements, provided that d and e cannot both be 0 and when d is greater than 0 and X is at least one of chromium, manganese and niobium, e is also greater than 0, the catalyst
15 support being at least one of silica, alumina, titania, magnesia, zinc aluminate ($ZnAl_2O_4$), magnesium aluminate ($MgAl_2O_4$), magnesia-modified alumina, zinc oxide-modified alumina, zirconium oxide-modified alumina, magnesia-modified silica, zinc oxide-modified silica, and zinc oxide.

2. The catalyst of Claim 1, wherein the catalyst is admixed with an
20 amount of an alkali metal carbonate or alkaline earth metal carbonate.

3. The catalyst of Claim 2, wherein the carbonate is an alkali metal carbonate and the amount of alkali metal carbonate is within a range of from greater than 0.1 millimole per hectogram to 75 millimole per hectogram based upon combined weight of the heterogeneous catalyst and the alkali metal carbonate.

25 4. The catalyst of Claim 2 or Claim 3 wherein the alkali metal carbonate is selected from sodium carbonate and lithium carbonate.

5. A process of converting a feedstream comprising a mixture of carbon monoxide, hydrogen and an alkylene to a product stream that comprises at least one oxygenate that has one carbon atom more than the alkylene, which process comprises
30 placing the feedstream in contact with the catalyst of any of Claims 1 through 4 under conditions sufficient to effect conversion of the feedstream to the product stream, said conditions including a temperature within a range of from 100°C TO 450°C, a pressure within a range of from 12 pounds per square inch gauge (82.7 kilopascals) to 4,000 pounds

per square inch gauge (27.6 megapascals), a gas hourly space velocity within a range of from 25 reciprocal hours to 25,000 reciprocal hours, and a feedstream ratio of ethylene to carbon monoxide to hydrogen within a range of from 0.01:10:10 to 10.0:0.01:0.01.

6. The process of Claim 5, wherein the alkylene is ethylene and the
5 oxygenate is a three carbon oxygenate selected from propanol and propanal.

TIONAL SEARCH REPORT

International application No PCT/US2012/021015

A. CLASSIFICATION OF SUBJECT MATTER		
INV. B01J37/02	B01J23/89	B01J23/00
C07C27/22	C07C5/03	C07C27/12
ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) B01J C07C		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WOLFGANG M. H. SACHTLER ET AL: "Catalytic site requirements for elementary steps in syngas conversion to oxygenates over promoted rhodium", THE JOURNAL OF PHYSICAL CHEMISTRY, vol. 90, no. 20, 1 September 1986 (1986-09-01), pages 4752-4758, XP55021591, ISSN: 0022-3654, DOI: 10.1021/j100411a009 cited in the application the whole document -----	1-6
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.		
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Date of the actual completion of the international search	Date of mailing of the international search report	
12 March 2012	19/03/2012	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Fischbach, Malaika	