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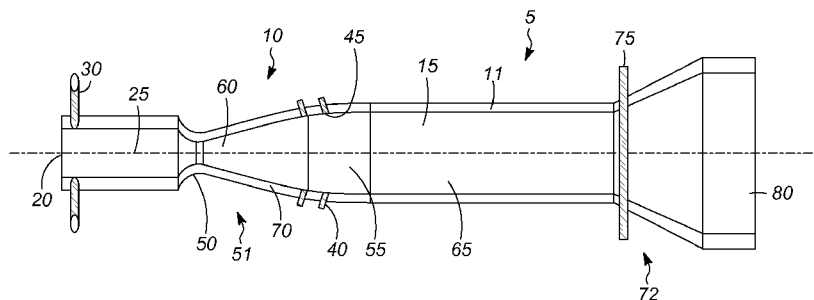
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(54) Title: THE PRODUCTION OF BUTADIENE FROM A METHANE CONVERSION PROCESS



(57) Abstract: Methods and systems are provided for converting methane in a feed stream to acetylene. The method includes processing the acetylene to form a stream having butadiene. The hydrocarbon stream is introduced into a supersonic reactor and pyrolyzed to convert at least a portion of the methane to acetylene. The reactor effluent stream is be treated to convert acetylene to butadiene. The method according to certain aspects includes controlling the level of carbon monoxide to prevent undesired reactions in downstream processing units.

THE PRODUCTION OF BUTADIENE FROM A METHANE
CONVERSION PROCESS

STATEMENT OF PRIORITY

5 **[0001]** This application claims priority to U.S. Application No. 61/691,351 which was filed on August 21, 2012, the contents of which are hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

10 **[0002]** A process is disclosed for producing chemicals useful for the production of polymers from the conversion of methane to acetylene using a supersonic flow reactor. More particularly, the process is for the production of butadiene.

BACKGROUND OF THE INVENTION

15 **[0003]** The use of plastics and rubbers are widespread in today's world. The production of these plastics and rubbers are from the polymerization of monomers which are generally produced from petroleum. The monomers are generated by the breakdown of larger molecules to smaller molecules which can be modified. The monomers are then reacted to generate larger molecules comprising chains of the monomers. An important example of these monomers are light olefins, including ethylene and propylene, which represent a large portion of the worldwide demand in the petrochemical industry. Light olefins, and other
20 monomers, are used in the production of numerous chemical products via polymerization, oligomerization, alkylation and other well-known chemical reactions. Producing large quantities of light olefin material in an economical manner, therefore, is a focus in the petrochemical industry. These monomers are essential building blocks for the modern petrochemical and chemical industries. The main source for these materials in present day
25 refining is the steam cracking of petroleum feeds.

[0004] A principal means of production is the cracking of hydrocarbons brought about by heating a feedstock material in a furnace has long been used to produce useful products,

including for example, olefin products. For example, ethylene, which is among the more important products in the chemical industry, can be produced by the pyrolysis of feedstocks ranging from light paraffins, such as ethane and propane, to heavier fractions such as naphtha. Typically, the lighter feedstocks produce higher ethylene yields (50-55% for ethane compared to 25-30% for naphtha); however, the cost of the feedstock is more likely to determine which is used. Historically, naphtha cracking has provided the largest source of ethylene, followed by ethane and propane pyrolysis, cracking, or dehydrogenation. Due to the large demand for ethylene and other light olefinic materials, however, the cost of these traditional feeds has steadily increased.

[0005] Energy consumption is another cost factor impacting the pyrolytic production of chemical products from various feedstocks. Over the past several decades, there have been significant improvements in the efficiency of the pyrolysis process that have reduced the costs of production. In a typical or conventional pyrolysis plant, a feedstock passes through a plurality of heat exchanger tubes where it is heated externally to a pyrolysis temperature by the combustion products of fuel oil or natural gas and air. One of the more important steps taken to minimize production costs has been the reduction of the residence time for a feedstock in the heat exchanger tubes of a pyrolysis furnace. Reduction of the residence time increases the yield of the desired product while reducing the production of heavier by-products that tend to foul the pyrolysis tube walls. However, there is little room left to improve the residence times or overall energy consumption in traditional pyrolysis processes.

[0006] More recent attempts to decrease light olefin production costs include utilizing alternative processes and/or feedstreams. In one approach, hydrocarbon oxygenates and more specifically methanol or dimethylether (DME) are used as an alternative feedstock for producing light olefin products. Oxygenates can be produced from available materials such as coal, natural gas, recycled plastics, various carbon waste streams from industry and various products and by-products from the agricultural industry. Making methanol and other oxygenates from these types of raw materials is well established and typically includes one or more generally known processes such as the manufacture of synthesis gas using a nickel or cobalt catalyst in a steam reforming step followed by a methanol synthesis step at relatively high pressure using a copper-based catalyst.

[0007] Once the oxygenates are formed, the process includes catalytically converting the oxygenates, such as methanol, into the desired light olefin products in an oxygenate to olefin

(OTO) process. Techniques for converting oxygenates, such as methanol to light olefins (MTO), are described in United States Patent No. 4,387,263, which discloses a process that utilizes a catalytic conversion zone containing a zeolitic type catalyst. United States Patent No. 4,587,373 discloses using a zeolitic catalyst like ZSM-5 for purposes of making light olefins. United States Patent Nos. 5,095,163; 5,126,308 and 5,191,141 on the other hand, disclose an MTO conversion technology utilizing a non-zeolitic molecular sieve catalytic material, such as a metal aluminophosphate (ELAPO) molecular sieve. OTO and MTO processes, while useful, utilize an indirect process for forming a desired hydrocarbon product by first converting a feed to an oxygenate and subsequently converting the oxygenate to the hydrocarbon product. This indirect route of production is often associated with energy and cost penalties, often reducing the advantage gained by using a less expensive feed material. In addition, some oxygenates, such as vinyl acetate or acrylic acid, are also useful chemicals and can be used as polymer building blocks.

[0008] Recently, attempts have been made to use pyrolysis to convert natural gas to ethylene. US Patent No. 7,183,451 discloses heating natural gas to a temperature at which a fraction is converted to hydrogen and a hydrocarbon product such as acetylene or ethylene. The product stream is then quenched to stop further reaction and subsequently reacted in the presence of a catalyst to form liquids to be transported. The liquids ultimately produced include naphtha, gasoline, or diesel. While this method may be effective for converting a portion of natural gas to acetylene or ethylene, it is estimated that this approach will provide only a 40% yield of acetylene from a methane feed stream. While it has been identified that higher temperatures in conjunction with short residence times can increase the yield, technical limitations prevent further improvement to this process in this regard.

[0009] While the foregoing traditional pyrolysis systems provide solutions for converting ethane and propane into other useful hydrocarbon products, they have proven either ineffective or uneconomical for converting methane into these other products, such as, for example ethylene. While MTO technology is promising, these processes can be expensive due to the indirect approach of forming the desired product. Due to continued increases in the price of feeds for traditional processes, such as ethane and naphtha, and the abundant supply and corresponding low cost of natural gas and other methane sources available, for example the more recent accessibility of shale gas, it is desirable to provide commercially

feasible and cost effective ways to use methane as a feed for producing butadiene and other useful hydrocarbons.

SUMMARY OF THE INVENTION

[0010] A method for producing acetylene according to one aspect is provided. The method generally includes introducing a feed stream portion of a hydrocarbon stream including methane into a supersonic reactor. The method also includes pyrolyzing the methane in the supersonic reactor to form a reactor effluent stream portion of the hydrocarbon stream including acetylene. The method further includes treating at least a portion of the hydrocarbon stream in a process for producing higher value products, such as butadiene.

[0011] According to another aspect, the process stream comprising acetylene is passed to an ethanol reactor operated at ethanol reaction conditions to form an effluent stream comprising ethanol. The ethanol is passed to a butadiene reactor operated at butadiene reaction conditions to convert the ethanol to a process stream comprising butadiene, water and hydrogen.

[0012] According to another aspect, a system is provided for producing acetylene from a methane feed stream. The system includes a supersonic reactor for receiving a methane feed stream and configured to convert at least a portion of methane in the methane feed stream to acetylene through pyrolysis and to emit an effluent stream including the acetylene. The system also includes a hydrocarbon conversion zone in communication with the supersonic reactor and configured to receive the effluent stream and convert at least a portion of the acetylene therein to another hydrocarbon compound in a product stream. The system includes a hydrocarbon stream line for transporting the methane feed stream, the reactor effluent stream, and the product stream. The system further includes a contaminant removal zone in communication with the hydrocarbon stream line for removing carbon monoxide from the reactor effluent stream comprising acetylene.

[0013] In one embodiment, the present invention comprises converting methane to acetylene through a supersonic reactor. The acetylene is passed to a dimerization reactor unit to generate a vinylacetylene stream. The vinylacetylene stream is passed to a hydrogenation reactor to convert the vinylacetylene to butadiene.

[0014] Other objects, advantages and applications of the present invention will become apparent to those skilled in the art from the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 is a side cross-sectional view of a supersonic reactor in accordance with various embodiments described herein;

[0016] FIG. 2 is a schematic view of a system for converting methane into acetylene and other hydrocarbon products in accordance with various embodiments described herein; and

[0017] FIG. 3 is a flow diagram of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] One proposed alternative to the previous methods of producing hydrocarbon products that has not gained much commercial traction includes passing a hydrocarbon feedstock into a supersonic reactor and accelerating it to supersonic speed to provide kinetic energy that can be transformed into heat to enable an endothermic pyrolysis reaction to occur. Variations of this process are set out in U.S. Pat. Nos. 4,136,015 and 4,724,272, and Russian Patent No. SU 392723A. These processes include combusting a feedstock or carrier fluid in an oxygen-rich environment to increase the temperature of the feed and accelerate the feed to supersonic speeds. A shock wave is created within the reactor to initiate pyrolysis or cracking of the feed. In particular, the hydrocarbon feed to the reactor comprises a methane feed. The methane feed is reacted to generate an intermediate process stream which is then further processed to generate a hydrocarbon product stream. A particular hydrocarbon product stream of interest is butadiene.

[0019] More recently, US Patent Nos. 5,219,530 and 5,300,216 have suggested a similar process that utilizes a shock wave reactor to provide kinetic energy for initiating pyrolysis of natural gas to produce acetylene. More particularly, this process includes passing steam through a heater section to become superheated and accelerated to a nearly supersonic speed. The heated fluid is conveyed to a nozzle which acts to expand the carrier fluid to a supersonic speed and lower temperature. An ethane feedstock is passed through a compressor and heater and injected by nozzles to mix with the supersonic carrier fluid to turbulently mix together at a Mach 2.8 speed and a temperature of 427°C. The temperature in the mixing section remains low enough to restrict premature pyrolysis. The shockwave reactor includes a pyrolysis section with a gradually increasing cross-sectional area where a standing shock wave is formed by back pressure in the reactor due to flow restriction at the outlet. The

shock wave rapidly decreases the speed of the fluid, correspondingly rapidly increasing the temperature of the mixture by converting the kinetic energy into heat. This immediately initiates pyrolysis of the ethane feedstock to convert it to other products. A quench heat exchanger then receives the pyrolyzed mixture to quench the pyrolysis reaction.

5 [0020] Methods and systems for converting hydrocarbon components in methane feed streams using a supersonic reactor are generally disclosed. As used herein, the term “methane feed stream” includes any feed stream comprising methane. The methane feed streams provided for processing in the supersonic reactor generally include methane and form at least a portion of a process stream that includes at least one contaminant. The methods and
10 systems presented herein remove or convert the contaminant in the process stream and convert at least a portion of the methane to a desired product hydrocarbon compound to produce a product stream having a reduced contaminant level and a higher concentration of the product hydrocarbon compound relative to the feed stream. By one approach, a hydrocarbon stream portion of the process stream includes the contaminant and methods and
15 systems presented herein remove or convert the contaminant in the hydrocarbon stream.

[0021] The term “hydrocarbon stream” as used herein refers to one or more streams that provide at least a portion of the methane feed stream entering the supersonic reactor as described herein or are produced from the supersonic reactor from the methane feed stream, regardless of whether further treatment or processing is conducted on such hydrocarbon
20 stream. The “hydrocarbon stream” may include the methane feed stream, a supersonic reactor effluent stream, a desired product stream exiting a downstream hydrocarbon conversion process or any intermediate or by-product streams formed during the processes described herein. The hydrocarbon stream may be carried via a process stream line 115, which includes lines for carrying each of the portions of the process stream described above.

25 The term “process stream” as used herein includes the “hydrocarbon stream” as described above, as well as it may include a carrier fluid stream, a fuel stream, an oxygen source stream, or any streams used in the systems and the processes described herein. The process stream may be carried via a process stream line 115, which includes lines for carrying each of the portions of the process stream described above.

30 [0022] Prior attempts to convert light paraffin or alkane feed streams, including ethane and propane feed streams, to other hydrocarbons using supersonic flow reactors have shown promise in providing higher yields of desired products from a particular feed stream than

other more traditional pyrolysis systems. Specifically, the ability of these types of processes to provide very high reaction temperatures with very short associated residence times offers significant improvement over traditional pyrolysis processes. It has more recently been realized that these processes may also be able to convert methane to acetylene and other useful hydrocarbons, whereas more traditional pyrolysis processes were incapable or inefficient for such conversions.

[0023] The majority of previous work with supersonic reactor systems, however, has been theoretical or research based, and thus has not addressed problems associated with practicing the process on a commercial scale. In addition, many of these prior disclosures do not contemplate using supersonic reactors to effectuate pyrolysis of a methane feed stream, and tend to focus primarily on the pyrolysis of ethane and propane. One problem that has recently been identified with adopting the use of a supersonic flow reactor for light alkane pyrolysis, and more specifically the pyrolysis of methane feeds to form acetylene and other useful products therefrom, includes negative effects that particular contaminants in commercial feed streams can create on these processes and/or the products produced therefrom. Previous work has not considered the need for product purity, especially in light of potential downstream processing of the reactor effluent stream. Product purity can include the separation of several products into separate process streams, and can also include treatments for removal of contaminants that can affect a downstream reaction, and downstream equipment.

[0024] In accordance with various embodiments disclosed herein, therefore, processes and systems for converting the methane to a product stream are presented. The methane is converted to an intermediate process stream comprising acetylene. The intermediate process stream is converted to a second process stream comprising either a hydrocarbon product, or a second intermediate hydrocarbon compound. The processing of the intermediate acetylene stream can include purification or separation of acetylene from by-products.

[0025] The removal of particular contaminants and/or the conversion of contaminants into less deleterious compounds has been identified to improve the overall process for the pyrolysis of light alkane feeds, including methane feeds, to acetylene and other useful products. In some instances, removing these compounds from the hydrocarbon or process stream has been identified to improve the performance and functioning of the supersonic flow reactor and other equipment and processes within the system. Removing these contaminants

from hydrocarbon or process streams has also been found to reduce poisoning of downstream catalysts and adsorbents used in the process to convert acetylene produced by the supersonic reactor into other useful hydrocarbons, for example hydrogenation catalysts that may be used to convert acetylene into ethylene. Still further, removing certain contaminants from a hydrocarbon or process stream as set forth herein may facilitate meeting product specifications.

[0026] In accordance with one approach, the processes and systems disclosed herein are used to treat a hydrocarbon process stream, to remove a contaminant therefrom and convert at least a portion of methane to acetylene. The hydrocarbon process stream described herein includes the methane feed stream provided to the system, which includes methane and may also include ethane or propane. The methane feed stream may also include combinations of methane, ethane, and propane at various concentrations and may also include other hydrocarbon compounds. In one approach, the hydrocarbon feed stream includes natural gas. The natural gas may be provided from a variety of sources including, but not limited to, gas fields, oil fields, coal fields, fracking of shale fields, biomass, and landfill gas. In another approach, the methane feed stream can include a stream from another portion of a refinery or processing plant. For example, light alkanes, including methane, are often separated during processing of crude oil into various products and a methane feed stream may be provided from one of these sources. These streams may be provided from the same refinery or different refinery or from a refinery off gas. The methane feed stream may include a stream from combinations of different sources as well.

[0027] In accordance with the processes and systems described herein, a methane feed stream may be provided from a remote location or at the location or locations of the systems and methods described herein. For example, while the methane feed stream source may be located at the same refinery or processing plant where the processes and systems are carried out, such as from production from another on-site hydrocarbon conversion process or a local natural gas field, the methane feed stream may be provided from a remote source via pipelines or other transportation methods. For example a feed stream may be provided from a remote hydrocarbon processing plant or refinery or a remote natural gas field, and provided as a feed to the systems and processes described herein. Initial processing of a methane stream may occur at the remote source to remove certain contaminants from the methane feed stream. Where such initial processing occurs, it may be considered part of the systems and

processes described herein, or it may occur upstream of the systems and processes described herein. Thus, the methane feed stream provided for the systems and processes described herein may have varying levels of contaminants depending on whether initial processing occurs upstream thereof.

5 **[0028]** In one example, the methane feed stream has a methane content ranging from 50 wt-% to 100 wt-%. In another example, the concentration of methane in the hydrocarbon feed ranges from 75 wt-% to 100 wt-% of the hydrocarbon feed. In yet another example, the concentration of methane ranges from 90 wt-% to 100 wt-% of the hydrocarbon feed.

10 **[0029]** In one example, the concentration of ethane in the methane feed ranges from 0 wt-% to 30 wt-% and in another example from 0 wt-% to 10 wt-%. In one example, the concentration of propane in the methane feed ranges from 0 wt-% to 10 wt-% and in another example from 0 wt-% to 2 wt-%.

15 **[0030]** The methane feed stream may also include heavy hydrocarbons, such as aromatics, paraffinic, olefinic, and naphthenic hydrocarbons. These heavy hydrocarbons if present will likely be present at concentrations of between 0 mol-% and 100 mol-%. In another example, they may be present at concentrations of between 0 mol-% and 10 mol-% and may be present at between 0 mol-% and 2 mol-%.

20 **[0031]** An aspect of this invention is the production of butadiene from the acetylene generated by the supersonic reactor. One method of producing butadiene according to the present invention is the formation of an intermediate process stream, with subsequent processing of the intermediate stream. The process comprises the formation of acetylene with the supersonic reactor. The acetylene stream is purified with the removal of carbon monoxide to generate an enriched acetylene stream. The enriched acetylene stream is passed to a hydration reactor, along with a water feed and a hydrogen stream feed, for a reaction of
25 the acetylene with water to form an effluent stream comprising ethanol. The ethanol is passed to butadiene reactor, where the ethanol is combined and dehydrated to form an effluent stream comprising butadiene, water and hydrogen.

30 **[0032]** A second method of forming butadiene from ethanol comprises splitting the ethanol effluent stream into a first ethanol stream and a second ethanol stream. The first ethanol stream is passed to an oxidation reactor to convert the ethanol to generate an effluent stream comprising acetaldehyde. The second ethanol stream and the acetaldehyde stream are passed to the butadiene reactor operated at butadiene reaction conditions to generate a

butadiene product stream. The product stream can be passed to a butadiene recovery unit, or purification unit. The conversion of acetylene to acetaldehyde can also be performed directly with a water stream in a hydration reactor, through appropriate controls and setting of reaction conditions.

5 **[0033]** The butadiene reaction conditions include carrying out the reaction over a catalyst at elevated temperatures. Temperatures for the butadiene reaction include temperatures in the range from 300°C to 350°C. Butadiene catalysts include Group 5 metals on a support. One example of a butadiene catalyst includes a tantalum promoted silica catalyst.

10 **[0034]** The reaction conditions for the hydration reactor include a second feed stream comprising steam. The reaction is carried out over an acidic catalyst at elevated temperatures and pressures. One example of the acidic catalyst is a phosphoric acid catalyst. The temperatures for the reaction range from 250°C to 400°C with a typical temperature around 300°C. The reaction is carried out under a pressure in the range from 6 to 8 MPa.

15 **[0035]** The reaction conditions for the butadiene reactor include carrying out the reaction over a catalyst at elevated temperatures. Preferred temperatures include the range of 400°C to 450°C. The catalyst used is a metal oxide catalyst or metal on alumina catalyst. Examples of preferred catalysts include MgO on silica, ZnO₂ and alumina, Zn on alumina, and mixtures of metal oxides on a support. One example of a metal oxide mixture includes a mixture of MnO and ZnO₂ on a support.

20 **[0036]** Another aspect of the present invention includes the production of butadiene through the generation of an intermediate ethylene stream. The process includes the conversion of methane in the supersonic reactor to form an effluent stream comprising acetylene. The acetylene is passed to an enrichment zone to remove carbon monoxide and other contaminants, to generate an enriched acetylene stream. The acetylene stream is passed
25 to a hydrogenation reactor to generate a hydrogenation effluent stream comprising ethylene. The ethylene stream is passed to a dimerization reactor to form an effluent stream comprising butenes. The butene stream is passed to a dehydrogenation reactor to generate an effluent stream comprising butadiene.

30 **[0037]** An aspect of this invention is the production of olefins from the acetylene generated by the supersonic reactor. The reactor converts a methane stream through pyrolysis to generate a reactor effluent stream comprising acetylene. The reactor effluent stream is passed to a hydroprocessing reactor to form a second process stream comprising

olefins. In one embodiment, the reactor effluent stream is passed to a reactor effluent treating unit to remove carbon oxides in the reactor effluent stream. Carbon oxides include carbon monoxide (CO) and carbon dioxide (CO₂). The reactor effluent treating unit can remove other contaminants, such as CO to a level below at least 1 vol-%, and preferable to below a level of 100 vol-ppm. The removal of CO before further processing is to limit or prevent other reactions that can lead to a reduction in the yields of olefins. The treating unit can comprise an adsorber. Adsorbers are known to those skilled in the art, and can be designed to adsorb polar compounds from a mixture comprising polar and non-polar compounds. In one embodiment, the hydroprocessing reactor is a hydrogenation reactor for converting acetylene to ethylene in the presence of hydrogen. The hydroprocessing reactor effluent stream can be passed to a light olefins recovery unit to separate ethylene and other olefins from the hydroprocessing reactor effluent stream.

[0038] Hydrogenation reactors comprise a hydrogenation catalyst, and are operated at hydrogenation conditions to hydrogenate unsaturated hydrocarbons. Hydrogenation catalysts typically comprise a hydrogenation metal on a support, wherein the hydrogenation metal is preferably selected from a Group VIII metal in an amount between 0.01 and 2 wt. % of the catalyst. Preferably the metal is platinum (Pt), palladium (Pd), or a mixture thereof. The support is preferably a molecular sieve, and can include zeolites such as zeolite beta, MCM-22, MCM-36, mordenite, faujasites such as X-zeolites and Y-zeolites, including B-Y-zeolites and USY-zeolites; non-zeolitic solids such as silica-alumina, sulfated oxides such as sulfated oxides of zirconium, titanium, or tin, mixed oxides of zirconium, molybdenum, tungsten, phosphorus and chlorinated aluminium oxides or clays. Preferred supports are zeolites, including mordenite, zeolite beta, faujasites such as X-zeolites and Y-zeolites, including BY-zeolites and USY-zeolites. Mixtures of solid supports can also be employed.

[0039] In one embodiment, the present invention generates butenes. The hydroprocessing effluent stream is passed to a second reactor. The second reactor can include a dimerization reactor for generating butenes. The dimerization catalysts can comprise any dimerization or oligomerization catalyst, with preferred oligomerization catalysts comprising organometallic catalyst. The organometallic catalysts preferably comprise a metal bonded to more than 1 organic ligand.

[0040] Dehydrogenation catalysts can comprise a metal on a support, and in particular a Group 6, 8, 9, 10, 11 metal on a support. Dehydrogenation catalysts can also include a alkali

or alkaline earth metal with the Group 8, 9, or 10 metal on the support, and more particularly a noble metal on a support. Support materials include, but are not limited to, alumina, silica alumina, zeolitic materials, and mixtures thereof. Dehydrogenation reaction conditions include pressures between 100 kPa and 2 MPa, a temperature between 200°C and 600°C, a liquid hourly space velocity between 0.1 and 40 hr⁻¹, and a mole ratio of hydrogen to hydrocarbon feed between 0.1 and 20. The dehydrogenation reaction is carried out under an atmosphere comprising hydrogen.

[0041] Dehydrogenation is an endothermic process, and heat for the endothermic process can be supplied from the heat generated in the pyrolysis reaction in the supersonic reactor.

[0042] One embodiment of the invention includes the production of butadiene in a more direct manner from acetylene. The process includes the formation of acetylene from the pyrolysis of methane. The acetylene is passed to a dimerization reactor at dimerization reaction conditions to form an effluent stream comprising vinylacetylene. The vinylacetylene is passed to a hydrogenation reactor at hydrogenation reaction conditions to generate a butadiene stream.

[0043] The process for forming acetylene from the methane feed stream described herein utilizes a supersonic flow reactor for pyrolyzing methane in the feed stream to form acetylene. The supersonic flow reactor may include one or more reactors capable of creating a supersonic flow of a carrier fluid and the methane feed stream and expanding the carrier fluid to initiate the pyrolysis reaction. In one approach, the process may include a supersonic reactor as generally described in U.S. Patent No. 4,724,272, which is incorporated herein by reference, in their entirety. In another approach, the process and system may include a supersonic reactor such as described as a “shock wave” reactor in U.S. Patent Nos. 5,219,530 and 5,300,216, which are incorporated herein by reference, in their entirety. In yet another approach, the supersonic reactor described as a “shock wave” reactor may include a reactor such as described in “Supersonic Injection and Mixing in the Shock Wave Reactor” Robert G. Cerff, University of Washington Graduate School, 2010.

[0044] While a variety of supersonic reactors may be used in the present process, an exemplary reactor 5 is illustrated in FIG. 1. Referring to FIG. 1, the supersonic reactor 5 includes a reactor vessel 10 generally defining a reactor chamber 15. While the reactor 5 is illustrated as a single reactor, it should be understood that it may be formed modularly or as separate vessels. A combustion zone or chamber 25 is provided for combusting a fuel to

produce a carrier fluid with the desired temperature and flowrate. The reactor 5 may optionally include a carrier fluid inlet 20 for introducing a supplemental carrier fluid into the reactor. One or more fuel injectors 30 are provided for injecting a combustible fuel, for example hydrogen, into the combustion chamber 25. The same or other injectors may be provided for injecting an oxygen source into the combustion chamber 25 to facilitate combustion of the fuel. The fuel and oxygen are combusted to produce a hot carrier fluid stream typically having a temperature of from 1200°C to 3500°C in one example, between 2000°C and 3500°C in another example, and between 2500°C and 3200°C in yet another example. According to one example the carrier fluid stream has a pressure of 1 atm or higher, greater than 2 atm in another example, and greater than 4 atm in another example.

[0045] The hot carrier fluid stream from the combustion zone 25 is passed through a converging-diverging nozzle 50 to accelerate the flowrate of the carrier fluid to above mach 1.0 in one example, between mach 1.0 and mach 4.0 in another example, and between mach 1.5 and 3.5 in another example. In this regard, the residence time of the fluid in the reactor portion of the supersonic flow reactor is between 0.5 to 100 ms in one example, 1 to 50 ms in another example, and 1.5 to 20 ms in another example.

[0046] A feedstock inlet 40 is provided for injecting the methane feed stream into the reactor 5 to mix with the carrier fluid. The feedstock inlet 40 may include one or more injectors 45 for injecting the feedstock into the nozzle 50, a mixing zone 55, an expansion zone 60, or a reaction zone or chamber 65. The injector 45 may include a manifold, including for example a plurality of injection ports.

[0047] In one approach, the reactor 5 may include a mixing zone 55 for mixing of the carrier fluid and the feed stream. In another approach, no mixing zone is provided, and mixing may occur in the nozzle 50, expansion zone 60, or reaction zone 65 of the reactor 5.

An expansion zone 60 includes a diverging wall 70 to produce a rapid reduction in the velocity of the gases flowing therethrough, to convert the kinetic energy of the flowing fluid to thermal energy to further heat the stream to cause pyrolysis of the methane in the feed, which may occur in the expansion section 60 and/or a downstream reaction section 65 of the reactor. The fluid is quickly quenched in a quench zone 72 to stop the pyrolysis reaction from further conversion of the desired acetylene product to other compounds. Spray bars 75 may be used to introduce a quenching fluid, for example water or steam into the quench zone 72.

[0048] The reactor effluent exits the reactor via outlet 80 and as mentioned above forms a portion of the hydrocarbon stream. The effluent will include a larger concentration of acetylene than the feed stream and a reduced concentration of methane relative to the feed stream. The reactor effluent stream may also be referred to herein as an acetylene stream as it includes an increased concentration of acetylene. The acetylene may be an intermediate stream in a process to form another hydrocarbon product or it may be further processed and captured as an acetylene product stream. In one example, the reactor effluent stream has an acetylene concentration prior to the addition of quenching fluids ranging from 2 mol-% to 30 mol-%. In another example, the concentration of acetylene ranges from 5 mol-% to 25 mol-% and from 8 mol-% to 23 mol-% in another example.

[0049] In one example, the reactor effluent stream has a reduced methane content relative to the methane feed stream ranging from 15 mol-% to 95 mol-%. In another example, the concentration of methane ranges from 40 mol-% to 90 mol-% and from 45 mol-% to 85 mol-% in another example.

[0050] The invention can include an acetylene enrichment unit having an inlet in fluid communication with the reactor outlet, and an outlet for a acetylene enriched effluent. One aspect of the system can further include a contaminant removal zone having an inlet in fluid communication with the acetylene enrichment zone outlet, and an outlet in fluid communication with the hydrocarbon conversion zone inlet, for removing contaminants that can adversely affect downstream catalysts and processes. One contaminant to be removed is CO to a level of less than 0.1 mole%, and preferably to a level of less than 100 ppm by vol. An additional aspect of the invention is where the system can include a second contaminant removal zone having an inlet in fluid communication with the methane feed stream and an outlet in fluid communication with the supersonic reactor inlet.

[0051] In one example the yield of acetylene produced from methane in the feed in the supersonic reactor is between 40 % and 95 %. In another example, the yield of acetylene produced from methane in the feed stream is between 50 % and 90 %. Advantageously, this provides a better yield than the estimated 40% yield achieved from previous, more traditional, pyrolysis approaches.

[0052] By one approach, the reactor effluent stream is reacted to form another hydrocarbon compound. In this regard, the reactor effluent portion of the hydrocarbon stream may be passed from the reactor outlet to a downstream hydrocarbon conversion

process for further processing of the stream. While it should be understood that the reactor effluent stream may undergo several intermediate process steps, such as, for example, water removal, adsorption, and/or absorption to provide a concentrated acetylene stream, these intermediate steps will not be described in detail herein.

5 [0053] Referring to FIG. 2, the reactor effluent stream having a higher concentration of acetylene may be passed to a downstream hydrocarbon conversion zone 100 where the acetylene may be converted to form another hydrocarbon product. The hydrocarbon conversion zone 100 may include a hydrocarbon conversion reactor 105 for converting the acetylene to another hydrocarbon product. While FIG. 2 illustrates a process flow diagram
10 for converting at least a portion of the acetylene in the effluent stream to ethylene through hydrogenation in hydrogenation reactor 110, it should be understood that the hydrocarbon conversion zone 100 may include a variety of other hydrocarbon conversion processes instead of or in addition to a hydrogenation reactor 110, or a combination of hydrocarbon conversion processes. Similarly, it illustrated in FIG. 2 may be modified or removed and are
15 shown for illustrative purposes and not intended to be limiting of the processes and systems described herein. Specifically, it has been identified that several other hydrocarbon conversion processes, other than those disclosed in previous approaches, may be positioned downstream of the supersonic reactor 5, including processes to convert the acetylene into other hydrocarbons, including, but not limited to: alkenes, alkanes, methane, acrolein, acrylic
20 acid, acrylates, acrylamide, aldehydes, polyacetylenes, benzene, toluene, styrene, aniline, cyclohexanone, caprolactam, propylene, butadiene, butyne diol, butandiol, C2-C4 hydrocarbon compounds, ethylene glycol, diesel fuel, diacids, diols, pyrrolidines, and pyrrolidones.

[0054] A contaminant removal zone 120 for removing one or more contaminants from
25 the hydrocarbon or process stream may be located at various positions along the hydrocarbon or process stream depending on the impact of the particular contaminant on the product or process and the reason for the contaminants removal, as described further below. For example, particular contaminants have been identified to interfere with the operation of the supersonic flow reactor 5 and/or to foul components in the supersonic flow reactor 5. Thus,
30 according to one approach, a contaminant removal zone is positioned upstream of the supersonic flow reactor in order to remove these contaminants from the methane feed stream prior to introducing the stream into the supersonic reactor. Other contaminants have been

identified to interfere with a downstream processing step or hydrocarbon conversion process, in which case the contaminant removal zone may be positioned upstream of the supersonic reactor or between the supersonic reactor and the particular downstream processing step at issue. Still other contaminants have been identified that should be removed to meet particular product specifications. Where it is desired to remove multiple contaminants from the hydrocarbon or process stream, various contaminant removal zones may be positioned at different locations along the hydrocarbon or process stream. In still other approaches, a contaminant removal zone may overlap or be integrated with another process within the system, in which case the contaminant may be removed during another portion of the process, including, but not limited to the supersonic reactor 5 or the downstream hydrocarbon conversion zone 100. This may be accomplished with or without modification to these particular zones, reactors or processes. While the contaminant removal zone 120 illustrated in FIG. 2 is shown positioned downstream of the hydrocarbon conversion reactor 105, it should be understood that the contaminant removal zone 120 in accordance herewith may be positioned upstream of the supersonic flow reactor 5, between the supersonic flow reactor 5 and the hydrocarbon conversion zone 100, or downstream of the hydrocarbon conversion zone 100 as illustrated in FIG. 2 or along other streams within the process stream, such as, for example, a carrier fluid stream, a fuel stream, an oxygen source stream, or any streams used in the systems and the processes described herein.

[0055] The present invention can be shown in FIG. 3, wherein a methane stream 204 is passed to a supersonic reactor unit 200. The unit 200 includes a feed of fuel 206, usually hydrogen and oxygen, for generating the supersonic flow. The reactor unit 200 pyrolyzes the methane to generate a reactor effluent stream 208 comprising acetylene, CO and H₂. The effluent stream 208 is processed in an acetylene enrichment zone 220 to remove non-acetylene components to a waste stream 222, and to generate an enriched acetylene stream 224. The acetylene stream 224 is passed to a second reactor unit 230, with a hydrogen stream 226 to generate second reactor effluent stream 232. The second reactor effluent stream 232 is passed to a third reactor 240 where a third process stream 234 is added to generate a butadiene process stream 242. In one embodiment, the second reactor unit 230 is an oxidation reactor to generate an ethanol stream 232. The ethanol stream 232 is passed to a butadiene reactor, and can be reacted at conditions for converting the ethanol to butadiene, or can be reacted with acetaldehyde to convert ethanol and acetaldehyde to butadiene. In

another embodiment, the second reactor unit 230 is a dimerization reactor to generate a vinylacetylene stream 232. The vinylacetylene stream is passed to the third reactor unit 240, where the third reactor unit is a hydrogenation reactor. The hydrogenation reactor generates the butadiene.

- 5 **[0056]** While there have been illustrated and described particular embodiments and aspects, it will be appreciated that numerous changes and modifications will occur to those skilled in the art, and it is intended in the appended claims to cover all those changes and modifications which fall within the true spirit and scope of the present disclosure and appended claims.

10

CLAIMS:

1. A method for producing butadiene comprising:

introducing a feed stream comprising methane into a supersonic reactor;

5 pyrolyzing the methane in the supersonic reactor to form a reactor effluent stream comprising acetylene;

passing the reactor effluent stream to a ethanol reactor at ethanol reaction conditions to form an ethanol reactor effluent stream; and

10 passing the ethanol effluent stream to a butadiene reactor at butadiene reactor conditions to generate a butadiene product stream.

2. The method of claim 1, wherein pyrolyzing the methane includes accelerating the hydrocarbon stream to a velocity of between mach 1.0 and mach 4.0 and slowing down the hydrocarbon stream to increase the temperature of the hydrocarbon process stream.

15 3. The method of claim 1, wherein pyrolyzing the methane includes heating the methane to a temperature of between 1200°C and 3500°C for a residence time of between 0.5 ms and 100 ms.

20 4. The method of claim 1, wherein treating the reactor effluent stream includes removing carbon dioxide to a level below 1000 wt-ppm of the hydrocarbon stream.

5. The method of claim 1, wherein the hydrocarbon stream includes a methane feed stream portion upstream of the supersonic reactor comprising natural gas.

25 6. The method of claim 1, wherein the ethanol reaction conditions include a temperature greater than 250°C.

7. The method of claim 1, wherein the ethanol reaction conditions include a pressure
30 between 6 and 8 MPa.

8. The method of claim 1, wherein the ethanol reaction conditions include a phosphoric acid catalyst.

5 9. The method of claim 1, wherein the ethanol reactor includes a steam feed to the ethanol reactor.

10. The method of claim 1, further comprising a methane enrichment zone positioned upstream of the supersonic reactor to remove at least some of the non-methane compounds from the feed stream prior to introducing the feed stream into the supersonic reactor.

10

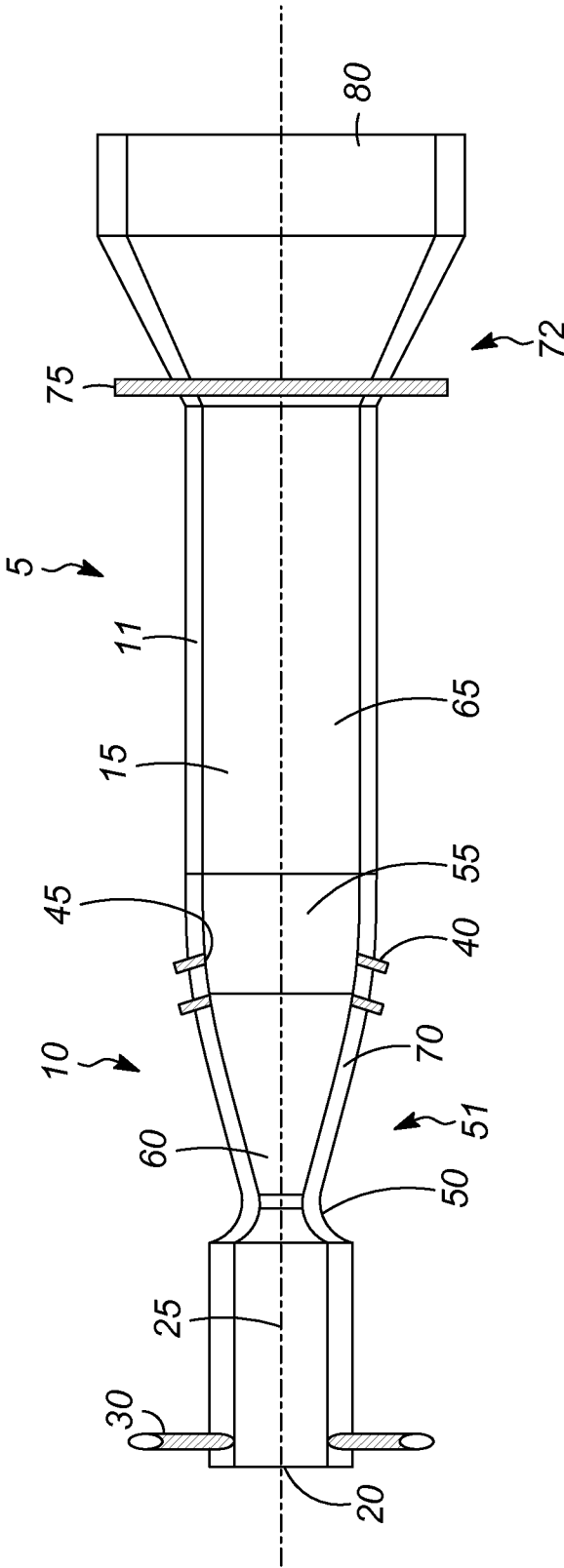


FIG. 1

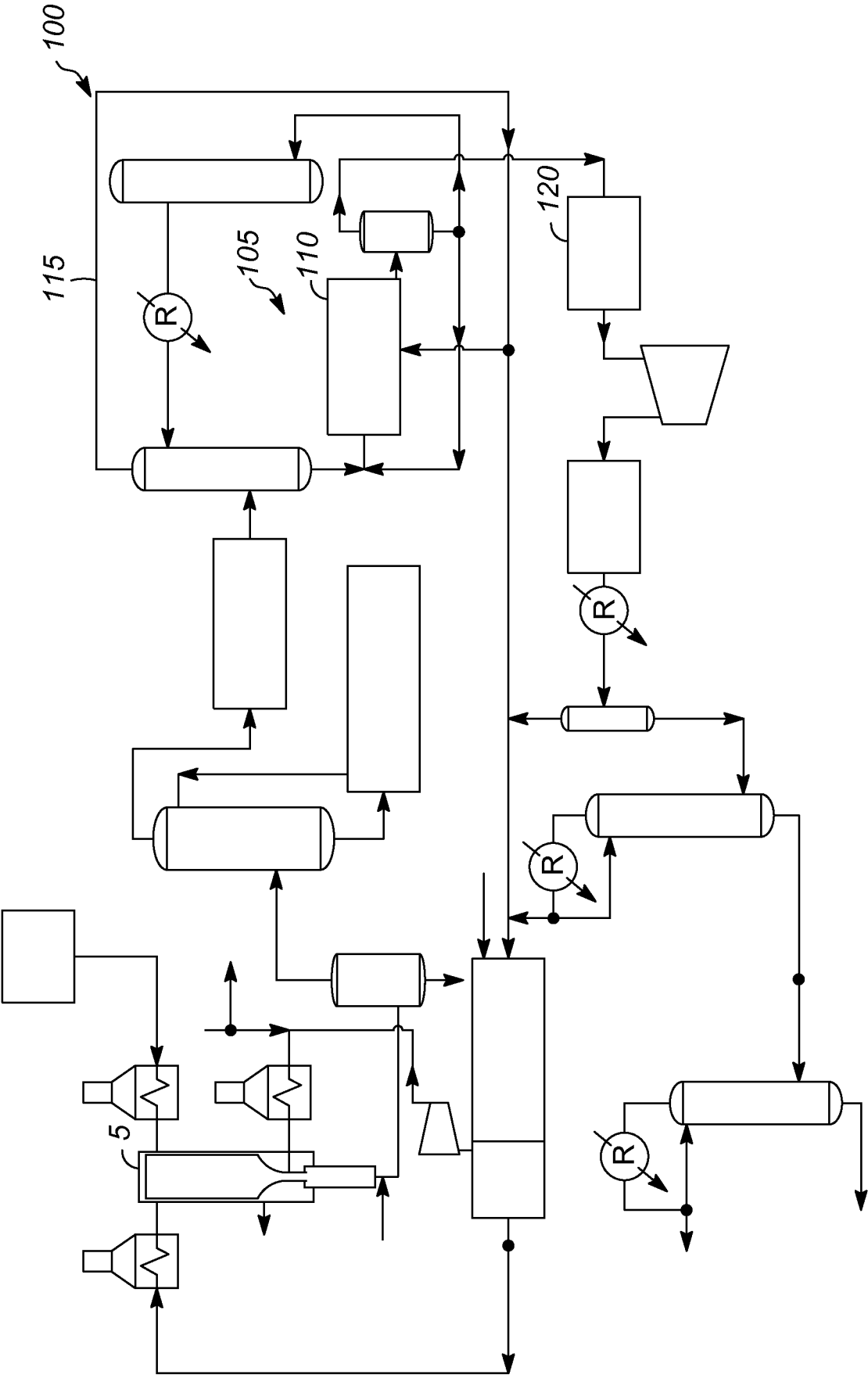


FIG. 2

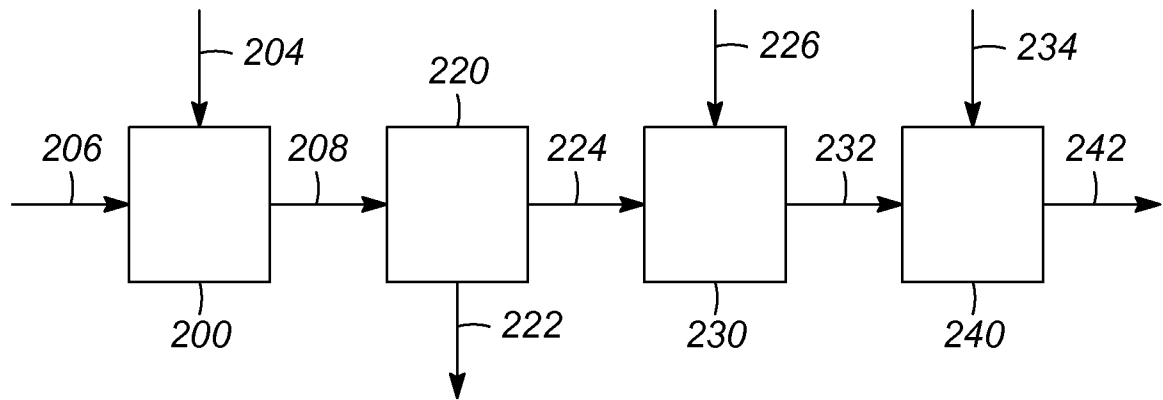


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2013/049298

A. CLASSIFICATION OF SUBJECT MATTER

C07C 11/24 (2006.01)
C07C 31/08 (2006.01)
C10G 9/00 (2006.01)
C07C 2/76 (2006.01)
C07C 29/03 (2006.01)
C07C 11/167 (2006.01)
C07C 1/20 (2006.01)

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)

C07C 11/24, 2/76, 1/20, 31/08, 29/03, 11/167, C10G 9/00

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 practicable, search terms used)

PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, Information Retrieval System of FIPS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4724272 A (ROCKWELL INTERNATIONAL CORPORATION) 09.02.1988, claims, col. 5-6	1-10
Y	RU 2373178 C2 (ZHUKOV ANATOLY VASILIEVICH et al.) 20.11.2009, abstract	1-10
Y	US 6953867 B2 (INNOVENE EUROPE LIMITED) 11.10.2005, claim 11, col. 9, lines 1-5	6-8
Y	RU 2440962 C1 (OBSHESTVO S OGRANICHENNOI OTVETSTVENNOSTIYU "UNISIT" (OOO "UNISIT")) 27.01.2012, abstract	1-10
Y	SU 392723 A (INSTITUT GAZA AN UKRAINSKOI SSR) 15.07.1983, col. 1, lines 25-28	5

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:		"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document but published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

24 September 2013 (24.09.2013)

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