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(54) **Title:** METHOD AND APPARATUS FOR PRODUCTION OF HYDROGEN USING ROTARY GENERATED THERMAL ENERGY

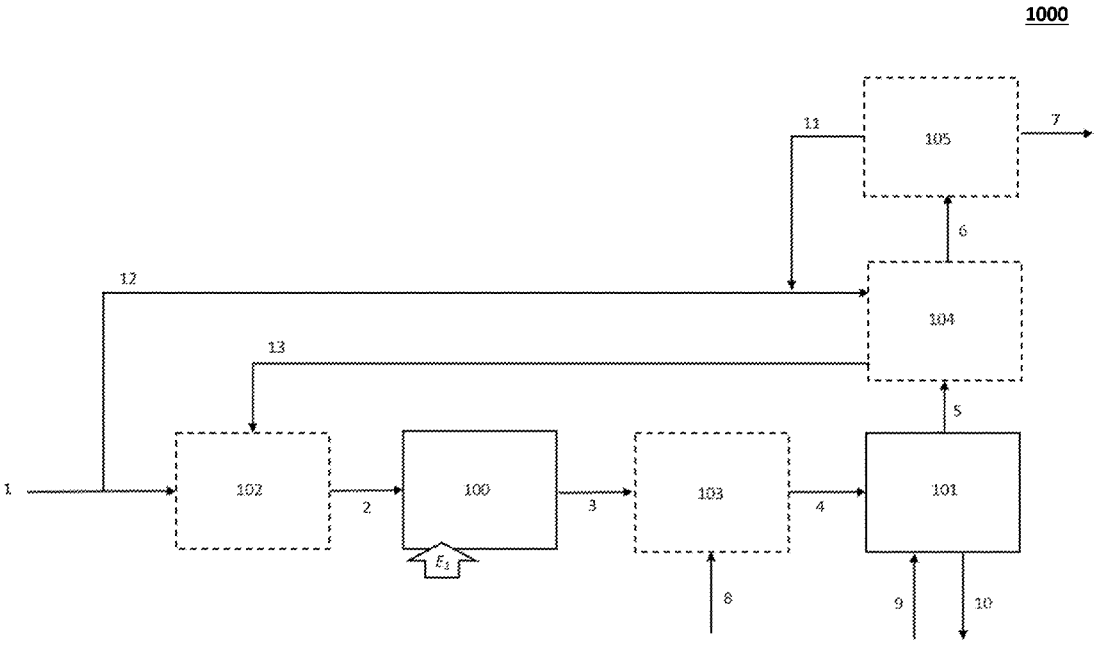


Figure 1

(57) **Abstract:** A method is provided for inputting thermal energy into fluidic medium in a process or processes related to production of hydrogen. The method comprises generating heated fluidic medium by at least one rotary apparatus (100) comprising a casing with at least one inlet and at least one exit, a rotor comprising at least one row of rotor blades arranged over a circumference of a rotor hub mounted onto a rotor shaft, and a stator configured as an assembly of stationary vanes arranged at least upstream of the at least one row of rotor blades. In the method, an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the rotary apparatus (100) by virtue of series of energy transformations occurring when said stream of fluidic medium passes through stationary and rotating components of said rotary apparatus (100), respectively. The method further comprises integration of said at least one rotary apparatus (100) into a heat-consuming process facility (1000) configured as a hydrogen production facility (1000)

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and further configured to carry out heat- consuming process or processes related to production of hydrogen at temperatures essentially equal to or exceeding 500 degrees Celsius (°C), and conducting an amount of input energy into the at least one rotary apparatus (100) integrated into the heat-consuming process facility (1000), the input energy comprises electrical energy. Related method, arrangement and facility for hydrogen production (1000) are further provided.

METHOD AND APPARATUS FOR PRODUCTION OF HYDROGEN USING ROTARY GENERATED THERMAL ENERGY

FIELD OF THE INVENTION

The present invention generally relates to systems and methods for inputting thermal energy (heat) into fluids. In particular, the invention relates to tools and processes for optimizing energy efficiency and reducing greenhouse gas and particle emissions in heat-consuming industrial processes related to production of hydrogen carried out at high and extremely high temperatures.

BACKGROUND

Industry and governments have been combating to find technologies to achieve significant reductions in greenhouse gas (GHG) emissions. For the purposes of global warming limitation, decarbonisation measures across a large number of key industrial sectors related for example to production of energy carriers must be undertaken. Many decarbonisation scenarios involve the use of hydrogen as a feedstock and/or fuel. About 90% of the global hydrogen production utilizes methane, the latter being the main component of natural gas.

Steam methane reforming (SMR) is apparently the most notable and widely used example of C1 chemistry and it is a dominant process for producing hydrogen from methane (rf. Equation 1a). Up to 95% of the world's hydrogen is produced through the SMR. In steam methane reforming, pretreated natural gas or other suitable feedstock gas such as shale gas, refinery off-gas or biogas is first pre-reformed with steam to decompose long-chain hydrocarbons into methane and syngas and then directed into a main reforming reactor, where methane is converted into hydrogen and carbon monoxide. Hydrogen yield can be further increased in a water gas shift (WGS) unit where part of the carbon monoxide reacts with water to produce hydrogen and carbon dioxide (Equation 1b).

(1a) $CH_4(g) + H_2O(g) \rightarrow CO + 3H_2$, $\Delta H = 206$ kJ/mol

(1b) $CO + H_2O \rightleftharpoons CO_2 + H_2$, $\Delta H = -41$ kJ/mol

Since reforming reaction (Eq. 1a) is endothermic, it requires a heat source. In a conventional SMR production plant, the heat is provided by an external furnace, which is typically fuel-fired. In an absence of carbon capture installation, after hydrogen recovery, a leftover stream containing methane, CO_2 and CO is routed to be used as fuel for the furnace, and all CO_2 is released to the atmosphere. On the other hand, the carbon capture is more efficient and hence more common from the SMR product stream (Eq. 1b) containing almost pure CO_2 as compared

to the flue gas exhaust stream which is a very dilute source of CO_2. As a result, even the SMR process employs the carbon capture, CO_2 originating from fuel burning in the furnace is still vented into the atmosphere. Therefore, the SMR process is one of the most significant sources of carbon dioxide in the atmosphere.

An alternative to SMR is an autothermal reforming (ATR) process (Equation 2a) yielding synthesis gas provided as a mixture of hydrogen and carbon monoxide in different ratios. The main difference between ATR and SMR is that the SMR does not use or require oxygen. In the reaction 2a, the heat is produced by partial oxidation of methane in a hydrocarbon feed stream.

(2a) $CH_4 + ½\ O_2 \rightarrow CO + 2H_2$, $\Delta H = -36$ kJ/mol

If methane and oxygen can be converted directly to CO and H_2 without side reactions, the equilibrium conversion would be almost 100%; however, in such as case the reaction requires very high temperatures. In most instances, the process of ATR proceeds through a series of reactions (Equations 2a-2c) which yield, along with carbon monoxide and hydrogen, also carbon dioxide and water:

(2b) $CH_4 + 2O_2 = CO_2 + 2H_2O$ (g) ($\Delta H = -803$ kJ/mol)

(2c) $CH_4 + O_2 = CO_2 + 2H_2$ ($\Delta H = -319$ kJ/mol)

Optimal conversion of methane is usually achieved by its partial oxidation at high temperatures (Eq. 2a). Compared to SMR (Eq. 1a), the ATR reactions of partial oxidation are exothermic and do not require an external heat source. Yet reaction yield is lower because part of the feed (methane / natural gas) is used as a fuel. However, there is no exhaust gases, and all of the CO_2 is concentrated in the product stream for carbon capture.

On the other hand, CO_2-free hydrogen may be produced in direct conversion/decomposition of methane (obtained in turn from natural gas or biogas) to hydrogen through a process of methane pyrolysis, in particular, if a renewable source of energy is used to provide heat required by the pyrolysis process. The process of thermal decomposition of methane produces solid carbon as the only by-product; therefore, the need in separation and storage of carbon oxides (CO, CO_2) is eliminated and the process is less complex as compared to the SMR. Accordingly, energy requirement per a molecule of H_2 produced through methane pyrolysis is almost half of that produced by SMR. Taken into account the abovesaid, the process of methane pyrolysis has a great potential in producing sustainable hydrogen.

Methane cracking (pyrolysis) is considered a bridge technology for CO_2-free production of hydrogen. In pyrolysis, methane and/or heavier hydrocarbons produce elemental carbon and CO_2 in an absence of oxygen and under high temperature. During the methane cracking process, unreacted methane is separated from hydrogen gas, and is recirculated to the pyrolysis reactor. Although the gas feedstock for methane cracking is mainly composed of CH_4, other hydrocarbons that may be also present are cracked in the same way as CH_4 by thermal splitting of C-H bonds.

Main reaction of methane pyrolysis is endothermic and ideally it produces gaseous hydrogen and solid carbon according to Equation 3:

(3) $CH_4\,(g) \rightarrow C\,(s) + 2\,H_2\,(g)$, $\Delta H = 75$ kJ mol

Process concepts for methane pyrolysis can be generally divided into three categories: (i) thermal (non-catalytic) decomposition; (ii) (thermo)catalytic decomposition, and (iii) plasma decomposition. In an absence of a suitable catalyst, decomposition reactions start at temperatures above ~700 °C. However, in order to achieve technically relevant reaction rates and methane conversion rates, these temperatures must be considerably higher: above apprx. 800 °C in catalytic processes, above apprx. 1000 °C in thermal processes, and up to about 2000 °C in plasma decomposition. Conventional gas reactor systems used for thermal and (thermo)catalytic decomposition of methane typically include tubular fixed-bed, moving-bed and fluidized-bed reactors.

In said conventional systems, a thermodynamic equilibrium between hydrogen and carbon is typically approached at temperatures between 500–1100 °C with residence times provided between 10–300 seconds depending on type of a catalyst. In an absence of the catalyst, residence times are significantly longer. Overall, in methane pyrolysis, residence time is a critical parameter that affects product distribution and selectivity. The residence time and temperature effect on properties of the carbon product and hence its further use.

Methane pyrolysis may also be used for the production of benzene and C2-hydrocarbons. Thermal decomposition of methane at high temperatures can yield ethylene, acetylene, benzene and hydrogen as main products provided that the reaction can be stopped before carbon is formed. In fact, methane can be converted directly to acetylene by pyrolysis or thermal coupling with high yields. The reaction is highly endothermic and requires a high-temperature heat supply. Main products of the reaction are typically acetylene and hydrogen. Excessive carbon formation can be avoided using short reaction times and low partial pressures of methane preferably by hydrogen dilution of the feed. Rapid quenching of the reaction mixture is also very important as indicated.

Accordingly, steam methane reforming can be performed with or without the use of catalyst. Non-catalytic reforming reaction proceeds through a pathway starting with methane pyrolysis, but, due to presence of steam, the intermediate products quickly convert to CO and H_2. Therefore, non-catalytic reforming proceeds at temperatures above 800 °C which are similar to those required for methane pyrolysis and are typically higher than the temperature of catalytic methane reforming (starting at about 700 °C).

However, existing heating technologies used to achieve high temperatures in methane pyrolysis are hindered with some common problems. In thermal and thermocatalytic decomposition, for example, heat required for the process is typically provided by (fuel-powered) external heaters as described above. Transfer of thermal energy through the reactor walls leads to quick formation of carbonaceous deposits, such as coke and soot, on hot surfaces, which causes operational difficulties and greatly impairs heat transfer. Solutions involving heating the gas in the reactor or in solutions utilizing concentrated solar power (thermal solar pyrolysis), the pyrolysis process often proceeds in an uncontrolled manner (in some instances pyrolysis reactions may be initiated already during (pre)heating) and thus causes fouling of reactor parts.

On the other hand, high temperatures required for hydrogen production from natural gas/methane by means of the processes described above generally represent one of the main reasons that restrain electrification of these processes. Although considered a suitable solution to reduce GHG emissions, electrification of the industrial processes remains hindered due to inability of current technologies and existing facility infrastructures to fulfil the needs in achieving sufficiently high temperatures.

A number of rotary solutions have been proposed for heating purposes. Thus, US 11,098,725 B2 (Sanger et al) discloses a hydrodynamic heater pump device operable to selectively generate a stream of heated fluid and/or pressurized fluid. Mentioned hydrodynamic heater pump is designed to be incorporated in an automotive vehicle cooling system to provide heat for warming a passenger compartment of the vehicle and to provide other capabilities, such as window deicing and engine cooling. The disclosed device may also provide a stream of pressurized fluid for cooling an engine. Disclosed technology is based on friction; and, since the fluid to be heated is liquid, the presented design is not suitable for conditions involving extreme turbulence of gas aerodynamics.

US 7,614,367 B1 (Frick) discloses a system and method for flamelessly heating, concentrating or evaporating a fluid by converting rotary kinetic energy into heat. Configured for fluid heating, the system may comprise a rotary kinetic energy generator, a rotary heating device and a primary heat exchanger all in closed-loop fluid communication. The rotary heating device

may be a water brake dynamometer. The document discloses the use of the system for heating water in offshore drilling or production platforms. However, the presented system is not suitable for heating gaseous media, neither is it feasible for use with high- and extremely high temperatures (due to liquid stability, vapor pressure, etc.).

Additionally, some rotary turbomachine-type devices are known to implement the processes of hydrocarbon (steam) cracking and aim at maximizing the yields of the target products, such as ethylene and propylene.

In this regard, an update in the field of technology related to design and manufacturing of efficient heating systems, in particular those suitable for production of hydrogen in industrial scale at high- and extremely high temperatures is still desired, in view of addressing challenges associated with raising temperatures of fluidic substances in efficient and environmentally friendly manner.

SUMMARY OF THE INVENTION

An objective of the present invention is to solve or to at least mitigate at least some of the problems arising from the limitations and disadvantages of the related art. One or more objectives are achieved by various embodiments of the methods for generation of a heated fluidic medium described herein, the rotary apparatuses and related uses as defined herein.

In an aspect, a method is provided for inputting thermal energy into a process or processes related to production of hydrogen in a hydrogen production facility.

In embodiment, the method comprises generation of a heated fluidic medium by at least one rotary apparatus integrated into the hydrogen production facility, said at least one rotary apparatus comprises a casing with at least one inlet and at least one exit, a rotor comprising at least one row of rotor blades arranged over a circumference of a rotor hub mounted onto a rotor shaft, and a plurality of stationary vanes arranged into an assembly at least upstream of the at least one row of rotor blades, wherein the method further comprises: integrating the at least one rotary apparatus into the hydrogen production facility configured to carry out process or processes related to hydrogen production at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C); conducting an amount of input energy into the at least one rotary apparatus integrated into the hydrogen production facility, the input energy comprising electrical energy, and operating the at least one rotary apparatus integrated into the hydrogen production facility such, that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by

virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary vanes and the at least one row of rotor blades, respectively, whereby a stream of heated fluidic medium is generated.

In an embodiment, the method comprises connecting, in said hydrogen production facility, the at least one rotary apparatus to at least one reactor or furnace configured to produce hydrogen from hydrocarbon-containing gas, such as hydrocarbon-containing feed gas. In embodiments, the at least one reactor or furnace is configured to carry out thermal and/or catalytic processes to generate hydrogen from the hydrocarbon-containing gas. In embodiments, the hydrogen production facility is a methane pyrolysis plant or a steam methane reforming (SMR) plant. In an embodiment, the hydrocarbon-containing gas is methane, natural gas or a mixture thereof.

In embodiment, the method comprises generation, by at least one rotary apparatus, of the fluidic medium heated to the temperature essentially equal to or exceeding about 500 degrees Celsius (°C), or to the temperature essentially equal to or exceeding about 1200 °C, or to the temperature essentially equal to or exceeding about 1700 °C.

In embodiment, the method comprises adjusting velocity and/or pressure of the stream of fluidic medium propagating through the rotary apparatus to produce conditions, at which the stream of the heated fluidic medium is generated.

In embodiments, in said method, the heated fluidic medium is generated by at least one rotary apparatus comprising two or more rows of rotor blades sequentially arranged along the rotor shaft.

In an embodiment, in said method, the heated fluidic medium is generated by at least one rotary apparatus further comprising a diffuser area arranged downstream of the at least one row of rotor blades, the method furthers comprises operating the at least one rotary apparatus integrated into the hydrogen production facility such, that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium successively passes through the stationary guide vanes, the at least one row of rotor blades and the diffuser area, respectively, whereby a stream of heated fluidic medium is generated. The diffuser area may be configured with or without stationary vanes.

In embodiments, in said method, the amount of thermal energy added to the stream of fluidic medium propagating through the rotary apparatus is controlled by adjusting the amount of input energy conducted into the at least one rotary apparatus integrated into the hydrogen production facility.

In embodiments, the method further comprises arranging an additional heating apparatus downstream of the at least one rotary apparatus and introducing a reactive compound or a mixture of reactive compounds to the stream of fluidic medium propagating through said additional heating apparatus, whereupon the amount of thermal energy is added to said stream of fluidic medium through exothermic reaction(s). In embodiment, the reactive compound or a mixture of reactive compounds is introduced to the stream of fluidic medium preheated to a predetermined temperature. In embodiment, the reactive compound or a mixture of reactive compounds is introduced to the stream of fluidic medium preheated to a temperature essentially equal to or exceeding about 1700 °C. In embodiment, preheating of the stream of fluidic medium to the predetermined temperature is implemented in the rotary apparatus.

In embodiment, the method comprises integrating at least two rotary apparatuses into the hydrogen production facility, said rotary apparatuses being connected in parallel or in series. In embodiment, the method comprises generation of the heated fluidic medium by at least two sequentially connected rotary apparatuses, wherein the stream of fluidic medium is preheated to a predetermined temperature in at least a first rotary apparatus in a sequence, and wherein said stream of fluidic medium is further heated in at least a second rotary apparatus in the sequence by inputting an additional amount of thermal energy into the stream of preheated fluidic medium propagating through said second rotary apparatus. In embodiment, in said method, in at least the first rotary apparatus in the sequence, the stream of fluidic medium is preheated to a temperature essentially equal to or exceeding about 1700 °C. n embodiment, in said method, the additional amount of thermal energy is added to the stream of fluidic medium propagating through said at least second rotary apparatus in the sequence by virtue of introducing the reactive compound or a mixture of compounds into said stream.

In embodiment, the method comprises introducing the reactive compound or a mixture of compounds into the process or processes related to hydrogen production.

In embodiment, in said method, the heated fluidic medium generated by the at least one rotary apparatus is selected from the group consisting of a feed gas, a recycle gas, a make-up gas, and a process fluid.

In embodiment, in said method, the fluidic medium that enters the rotary apparatus is an essentially gaseous medium.

In embodiment, the method comprises generation of the heated fluidic medium in the rotary apparatus. In embodiment, the heated fluidic medium generated in the rotary apparatus is a hydrocarbon-containing (feed) gas. In embodiments, the heated fluidic medium comprises or consist of methane, natural gas or a mixture of methane and natural gas. In embodiments, the

heated fluidic medium contains any one of C2-C4 alkanes (ethane, propane, butanes) or a mixture thereof, and/or any one of suitable longer-chain hydrocarbons. In embodiment, the heated fluidic medium generated in the rotary apparatus is a gaseous medium other than the hydrocarbon-containing (feed) gas, such as any one of air, steam (H_2O), nitrogen gas (N_2), or any combination thereof. In embodiments, the heated fluidic medium generated in the rotary apparatus is a recycle gas recycled from exhaust gases generated during hydrogen production process(es) in the hydrogen production facility.

In embodiment, the method further comprises generation of the heated fluidic medium outside the rotary apparatus through a process of heat transfer between the heated fluidic medium generated in the rotary apparatus and a stream of fluidic medium bypassing the rotary apparatus. In embodiment, the method comprises generation of the heated fluidic medium, provided as heated hydrocarbon-containing (feed) gas, outside the rotary apparatus through a process of heat transfer between the heated fluidic medium other than the hydrocarbon-containing (feed) gas generated in the rotary apparatus and a stream of fluidic medium provided as hydrocarbon-containing (feed) gas and bypassing the rotary apparatus.

In embodiment, the method further comprises increasing pressure in the stream of fluidic medium propagating through the rotary apparatus.

In embodiment, in said method, the amount of electrical energy conducted as the input energy into the at least one rotary apparatus integrated in the hydrogen production facility is within a range of about 5 percent to 100 percent.

In embodiment, in said method, the amount of electrical energy conducted as the input energy into the at least one rotary apparatus integrated in the hydrogen production facility is obtainable from a source of renewable energy or a combination of different sources of energy, optionally, renewable energy.

In embodiment, in said method, the at least one rotary apparatus is utilized to balance variations, such as oversupply and shortage, in the amount of electrical energy (obtained through supply and/or production, for example), optionally renewable electrical energy, by virtue of being integrated into the hydrogen production facility together with an at least one non-electrical energy operable heater device.

According to an embodiment, the method for inputting thermal energy into a process or processes related hydrogen production, which comprises generation of a heated fluidic medium by at least one rotary apparatus integrated into a hydrogen production facility, improves energy efficiency or reduces greenhouse gas and particle emissions, or both.

In another aspect, a hydrogen production facility is provided, said hydrogen production facility comprising at least one rotary apparatus configured to generate a heated fluidic medium and at least one heat-consuming unit configured as a reactor or furnace configured to carry out a process of processes related to hydrogen production, in accordance with the present disclosure.

In an embodiment, the hydrogen production facility comprises at least one reactor or furnace configured to produce hydrogen from hydrocarbon-containing gas at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C) and at least one rotary apparatus configured to generate a heated fluidic medium for inputting thermal energy into said at least one reactor or furnace, the at least one rotary apparatus comprising: a casing with at least one inlet and at least one exit, a rotor comprising at least one row of rotor blades arranged over a circumference of a rotor hub mounted onto a rotor shaft, and a plurality of stationary vanes arranged into an assembly at least upstream of the at least one row of rotor blades, wherein said at least one rotary apparatus is configured to receive an amount of input energy, the input energy comprising electrical energy, and wherein the at least one rotary apparatus is further configured to operate such that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary guide vanes and the at least one row of the rotor blades, respectively, whereby a stream of heated fluidic medium is generated.

In some configurations, within the hydrogen production facility, the at least one rotary apparatus is further configured to supply heated fluidic medium into least one heat-consuming unit configured as any one of: a heater, a burner, an oven, an incinerator, a dryer, a boiler, a conveyor device, or a combination thereof, and the at least one rotary apparatus is connected to any one of these heat-consuming units or any combination thereof within the hydrogen production facility.

In embodiments, in said hydrogen production facility, the at least one rotary apparatus comprises two or more rows of rotor blades sequentially arranged along the rotor shaft. In an embodiment, stationary vanes arranged into the assembly upstream of the at least one row of rotor blades are configured as stationary guide vanes. In an embodiment, the at least one rotary apparatus further comprises a diffuser area arranged downstream of the at least one row of rotor blades. The diffuser area may be configured with or without stationary diffuser vanes. In some configurations, vaned diffuser may be implemented as a plurality of stationary vanes arranged into an assembly downstream of the at least one row of rotor blades.

In an embodiment, the at least one rotary apparatus provided within said hydrogen production facility is further configured to increase pressure in the fluidic stream propagating therethrough.

In some configurations, the at least one rotary apparatus provided within said hydrogen production facility is configured to implement a fluidic flow, between the inlet and the exit, along a flow path established in accordance with any one of: an essentially helical trajectory formed within an essentially toroidal-shaped casing; an essentially helical trajectory formed within an essentially tubular casing, an essentially radial trajectory, and along the flow path established by virtue of the stream of fluidic medium in the form of two spirals rolled up into vortex rings of right and left directions.

In embodiments, the hydrogen production facility is configured to implement a process or processes related to production of hydrogen through a method according to the previous aspect and related embodiments. In embodiment, the hydrogen production facility is configured as a methane pyrolysis plant or a steam methane reforming (SMR) plant.

In a further aspect, an assembly is provided and comprises at least two rotary apparatuses according to some previous aspect, said rotary apparatuses being connected in parallel or in series.

In a further aspect, an arrangement is provided and comprises at least one rotary apparatus according to some previous aspect, said at least one rotary apparatus being connected to at least one reactor or furnace.

In a further aspect, a hydrogen production facility is provided and is configured to implement a hydrogen production process through a method according to some previously defined aspects and embodiments; and it comprises at least one rotary apparatus as defined herein.

In some further aspects, uses of the method and the facility, according to some previous aspects and embodiments are provided, and are defined in the independent claims 40-44

In a further aspect, a method for production of hydrogen is provided, in accordance with what is defined in the independent claim 45. The method comprises inputting thermal energy into a process or processes related to producing hydrogen in a hydrogen production facility in accordance with the method defined in some previous aspect and related embodiments.

In an aspect, a method for production of hydrogen is provided, the method comprising generation of a heated fluidic medium by at least one rotary apparatus integrated into a hydrogen production facility, the at least one rotary apparatus comprising: a casing with at least one inlet and at least one exit, a rotor comprising at least one row of rotor blades arranged over

a circumference of a rotor hub mounted onto a rotor shaft, and a plurality of stationary vanes arranged into an assembly at least upstream of the at least one row of rotor blades, wherein an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary vanes and the at least one row of rotor blades, respectively, whereby a stream of heated fluidic medium is generated, the method further comprising: conducting an amount of input energy into the at least one rotary apparatus integrated into the hydrogen production facility, the input energy comprising electrical energy, supplying the stream of heated fluidic medium generated in the at least one rotary apparatus into the hydrogen production facility, and operating said at least one rotary apparatus and said hydrogen production facility to carry out hydrogen production at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C).

The utility of the present invention arises from a variety of reasons depending on each particular embodiment thereof.

Overall, embodiments of the invention offer an electrified rotary fluid heater to generate high temperature fluids, such as gases, which can be further used, instead of fuel-fired heaters for example, in a variety of heat-consuming processes related to production of hydrogen. Production of hydrogen typically employs fuel-fired heaters to heat fluids to the temperatures needed for conversion of methane to hydrogen for example. The invention presented herewith enables replacing conventional fuel fired-heaters, by rotary apparatus(-es). The presented method further enables inputting thermal energy into heat-consuming utilities such as reactors and/or furnaces adapted to accommodate the reactions related to hydrogen production and operating at high- and extremely high temperatures, such as temperatures generally exceeding 500 °C. These reactors and/or furnaces have high demand for thermal energy and hence for heat consumption. The invention offers apparatuses and methods for heating fluidic substances to the temperatures within a range of about 500 °C to about 2000 °C, i.e. the temperatures used in hydrogen production industry.

In the method, the advantages accompanied by replacing fired heaters with the rotary apparatus include at least:

- Support for electrified heating;
- Elimination or at least significant reduction of greenhouse gas (such as NO, CO_2, CO, NO_X), other harmful components (such as for example HCl, H_2S, SO_2, and heavy metals) originating from fuels, particle emissions and soot emissions;

- Reduced volume of a heater: the volume of the rotary apparatus is at least one order of magnitude smaller as compared to the volume of conventional process heaters or heat exchangers;
- Decreased investment costs;
- Improved safety in case of using flammable, hazardous fluids / gases;
- Feasibility in handling large volumes of gases;
- Absence of pressure drop;
- Possibility of using the rotary (heater) apparatus also for compression of gases (a blower function);
- Independency on temperature difference in direct heating of gases. Temperature rise in the rotary apparatus can be in range of about 10 to 1700 °C or more;
- Possibility for using the rotary apparatus in indirect heating of fluids optionally by optimizing temperature difference in heat exchanger(s);
- Possibility for at least partial recycling of hot process gases, thus improving and making simpler the heat recovery and improving energy efficiency;
- Possibility for further raising the temperature of gases to be heated by adding reactive chemicals which further increase the gas temperature up to e.g. 2000 °C or higher by exothermic reactions.

In embodiments, the rotary apparatus can be used to replace conventional fired heaters or process furnaces for direct or indirect heating in process applications related to hydrogen production. Traditionally such heat has been mainly produced through burning of fossil fuels leading to significant CO_2 emissions. Replacing fossil fuels with wood or other bio-based materials has significant resource limitations and other significant environmental implications such as sustainable land use. With increased cost-efficiency of development of renewable electricity, such as for example rapid development of wind and solar power, it is possible to replace the fossil fuel firing with the rotary apparatus powered with renewable electricity, which would in turn significantly reduce greenhouse gas emissions. The rotary apparatus allows electrified heating of fluids to the temperatures up to 1700 °C and higher. Such temperatures are difficult or impossible to reach with current electrical heating applications.

The invention thus enables reduction of greenhouse gas- (CO, CO_2, NO_x) and particle emissions. By using the rotary apparatus, it is also possible to have closed or semi-closed heating loops for the hydrogen production processes, and to further improve energy efficiency of these processes by reducing heat losses through recycling flue gases. On the contrary, in conventional heaters, flue gases can be recycled only partly.

In steam methane reforming, by providing the (electrified) rotary fluid heater apparatus in place of a conventional furnace, formation of flue gases and hence formation of the dilute CO_2 source (typically resulting from fuel burning) can be avoided. Combined with already available techniques for carbon capture from the SMR reaction (see Eq. 1b providing a pure source of CO_2), the method disclosed hereby enables achieving a CO_2 emission-free hydrogen production.

Integration of the rotary apparatus into methane pyrolysis solves or at least alleviates a problem related to formation of carbon deposits on hot heating surfaces in furnaces or other type of heaters due to long residence time. Residence time of feedstock gas, hereby, methane, in the apparatus can be minimized such that an extent of carbon formation will be significantly decreased. Additionally or alternatively, the temperature of said feedstock gas propagating through the rotary apparatus can be increased by arranging rotor unit(s) within the apparatus such that conversion rate of the reactions is improved and carbon deposits do not interfere with the rotating parts of the machine. The rotary apparatus can be used in methane pyrolysis in connection with different type of pyrolysis reactors with or without catalysts to reach sufficient conversion of methane.

The rotary apparatus can be used for direct heating of process gases, inert gases, air or any other gases or for indirect heating of process fluids (liquid, vapor, gas, vapor/liquid mixtures etc.). For example, the rotary apparatus can be used for direct heating of a recycle gas recycled from exhaust gases generated during the hydrogen production process.

Heated fluid generated in said rotary apparatus can be further used for heating any one of gases, vapor, liquid, and solid materials. Hence, hot gases generated in the rotary apparatus can be used for heating solid materials or they can be used for heating the feed in a packed reactor adapted for any one of catalytic and thermal processes. The method offered herewith further allows for using hot gases as heating media in heat exchangers in order to indirectly heat process gases or liquids. Additional uses, such as in an evaporator, are not excluded.

The rotary apparatus can at least partly replace- or it can be combined with (e.g. as preheater) multiple types of furnaces, heaters, kilns, gasifiers, and reactors that are traditionally fired or heated with solid, liquid or gaseous fossil fuels or in some cases bio-based fuels, including reactors and furnaces used in hydrogen production. Heated gases can be flammable, reactive, or inert and can be recycled back to the rotary apparatus. In addition to its heating function, the rotary apparatus may also act as a blower (combined heater–blower functionality), thus allowing to increase pressure and to recycle gas in various applications, such as for example in catalytic fluidized bed reactors.

In the method offered herewith, the rotary apparatus can be used in heating methane-containing feed to required operating temperature in an almost complete absence of CO_2 emissions (the latter is possible when the rotary apparatus uses renewable electricity). Residence times in the rotary apparatus are extremely short, which improves selectivity and reduces formation of reaction by-products. Short residence times also minimize coke formation and extends operating periods between scheduled decoking procedures. In the method according to the present disclosure, a reactor for actual hydrogen production (e.g. the methane steam reformer) and a heater (the rotary apparatus) are separated, which allows for additional flexibility in operation. According to the embodiments, the reactor or furnace for hydrogen production can be connected to the rotary apparatus(-es) in parallel or in series, which further allows for switching between thermal reactors for carbon removal and catalytic reactors for decoking and cleaning in the same production process.

Additionally, the present solution enables improved optimization of the temperature difference(s) in the heat exchangers in indirect heating.

The invention further provides for flexibly using electrical energy, such as electrical energy obtainable from renewable sources. Production of renewable energy varies on daily basis and even on hourly basis. The invention allows for balancing renewable electricity production by integration of the rotary apparatus disclosed herewith with conventional fuel-operated (fuel-fired) heaters to provide heat to a variety of processes involved in hydrogen production.

The invention further enables a reduction in the on-site investment costs as compared to traditional fossil fired furnaces.

The expression “a number of” refers hereby to any positive integer starting from one (1), e.g. to one, two, or three. The expression “a plurality of” refers hereby to any positive integer starting from two (2), e.g. to two, three, or four. The terms “first” and “second”, are used hereby to merely distinguish an element from another element without indicating any particular order or importance, unless explicitly stated otherwise.

The term “gasified” is utilized hereby to indicate matter being converted into a gaseous form by any possible means.

Different embodiments of the present invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram representing, at 1000, a layout for a hydrogen production facility configured to implement a method according to the embodiments.

Figs. 2A-2F are exemplary layouts of arranging rotary apparatus(es) 100 within the hydrogen production facility, according to the embodiments.

Fig. 3 is schematic representation of a facility and method for hydrogen production via a process of methane pyrolysis, according to the embodiments.

Figs. 4A-4C are schematic representations of facilities and method(s) for hydrogen production via a process of steam methane reforming, according to the embodiments.

Figs. 5A and 5B are layouts of integrating the rotary apparatus(es) 100 into facilities and methods according to the embodiments.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Detailed embodiments of the present invention are disclosed herein with the reference to accompanying drawings.

Fig. 1 is a block diagram representing, at 1000, a layout for a hydrogen production facility configured to implement a method according to the embodiments. Figs. 2-4 describe apparatuses and methods according to the embodiments. Figs. 1-4 and related examples serve illustrative purposes and are not intended to limit applicability of the inventive concept to the layouts expressly presented in this disclosure. Block diagram sections shown by dotted lines may be optional in some configurations.

In embodiments, the heat-consuming facility 1000 is represented with an industrial plant, a factory, or any industrial system comprising equipment designed to perform an industrial process or a series of industrial processes aiming at producing hydrogen and optionally synthesis gas (syngas) from essentially raw materials, such as for example natural gas, biogas, and/or any other hydrocarbon-containing feedstock. In embodiments, the facility can be further adapted to produce fuels and hydrocarbons, such as for example ethane, ethylene, acetylene, benzene, and the like. In this context, the term “fuel(s)” relates to products used as energy carrier, and the term “chemical(s)” relates to any other product that is not used as a fuel. Heat-consuming process(es) and related operational units configured to carry out heat-consuming processes related to production of at least hydrogen within the facility 1000 and referred to as heat-consuming process unit(s)/utility(/ies) is/are collectively designated by a reference numeral 101. The facility 1000 may comprise a number of operational units 101 configured to perform same or different heat-consuming processes. In embodiments, the operational unit 101

comprises or consists of at least one heat-consuming device configured to carry out a heat-consuming process. In embodiments, the operational unit 101 is configured as a reactor device configured to carry out a reaction or a series of reactions aiming at hydrogen production from methane and/or raw feedstock(s), such as for example natural gas or biogas, through thermal and/or catalytic processes.

The heat-consuming process facility 1000 is thus configured to carry out a heat-consuming industrial process or processes 101 at temperatures essentially equal to- or exceeding 500 degrees Celsius (°C). In the present disclosure, the heat-consuming industrial process(es) is/are those involved in production of hydrogen, carbon and optionally synthesis gas from hydrocarbon feedstock, through the processes of methane steam reforming or methane pyrolysis. In embodiments, the facility 1000 is configured to carry out the heat-consuming industrial process(es) at temperatures within a range of 500–1700 °C. In embodiments, the facility 1000 is configured to carry out the heat-consuming industrial process(es) which start at temperatures essentially within a range of about 800–900 °C or higher. In embodiments, the facility 1000 is configured to carry out the heat-consuming industrial process(es) at temperatures essentially equal to- or exceeding 1000 °C. In embodiments, the facility 1000 is configured to carry out the heat-consuming industrial process(es) which start at temperatures essentially within a range of about 1100–1200 °C or higher. In embodiments, the facility 1000 is configured to carry out the heat-consuming industrial process(es) at temperatures essentially equal to- or exceeding 1200 °C. In embodiments, the facility is configured to carry out the heat-consuming industrial process(es) at temperatures within a range of about 1300–1700 °C. In embodiments, the facility is configured to carry out the heat-consuming industrial process(es) at temperatures essentially equal to- or exceeding 1500 °C. In embodiments, the facility is configured to carry out the heat-consuming industrial process(es) at temperatures essentially equal to- or exceeding 1700 °C. In some embodiments, the facility can be configured to carry out industrial process(es) at temperatures that exceed 1700 °C, such as at 2000 °C or higher, such as within a range of about 1700 °C to about 2500 °C. The facility can be configured to carry out industrial process(es) at about 1700 °C, at about 1800 °C, at about 1900 °C, at about 2000 °C, at about 2100 °C, at about 2200 °C, at about 2300 °C, at about 2400 °C, at about 2500 °C, and at any temperature value falling in between the above-mentioned temperature points. It should be pointed out that the facility 1000 is not excluded from carrying out of at least a part of industrial processes at temperatures below 500 °C.

Production of hydrogen is typically associated with high thermal (heat) energy demand and consumption and, in conventional solutions, produce considerable industrial emissions such as carbon dioxide into the atmosphere. The present disclosure offers methods and apparatuses for inputting thermal energy into the hydrogen production related processes 101 which have high

heat energy demand, whereby energy efficiency in said processes can be markedly improved and/or the amount of air pollutants released into the atmosphere reduced. Layout 1000 (Fig. 1) schematically outlines these improved facility and method.

In embodiments, the method comprises generation of a heated fluidic medium by virtue of a rotary heater unit 100 comprising or consisting of at least one rotary apparatus, hereafter, the apparatus 100. For the sake of clarity, the rotary heater unit is designated in the present disclosure by the same reference number, 100, as the rotary apparatus. The rotary heater unit is preferably integrated into the process facility 1000. In an embodiment, the heated fluidic medium is produced by the at least one rotary apparatus; however, a plurality of rotary apparatuses may be used in series or in parallel.

The rotary apparatus 100 can be provided as a standalone apparatus or as a number of apparatuses arranged in series (in sequence) or in parallel. One or more apparatuses may be connected to a common heat-consuming unit 101. Connection may be direct or through a number of heat exchangers.

The heat-consuming unit(s) 101 is/are provided as one or more reactors and/or furnaces adapted to implement reactions aiming at hydrogen production from hydrocarbon-containing feed, such as for example methane-containing feed, and operating with and/or without catalyst to implement catalytic and/or thermal processes, respectively. The reactor can be for example a fixed-bed reactor, a fluidized-bed reactor, or any other appropriate type of reactor device. In some configurations, thermal energy of the fluid, such as gas, heated in 100 is used to run endothermic reactions in the unit 101. In such as case, the fluid heated in 100 forms, at least partly, the process fluid of 101. In some other configurations, the fluid heated in 100 transfers its thermal energy to a process fluid used in the heat-consuming unit/process 101 to indirectly provide heat of reaction to said process. In an event of indirect heating, the fluid heated in 100 may be same or different than the process fluid used in the heat-consuming unit/process 101; however, typically it is different. In configurations which involve said indirect heating, the thermal energy added into the fluid in the rotary apparatus 100 is transferred to the heat-consuming unit/process 101 through the use of so-called “heat exchanger”-type configurations represented, in the present context, with any existing fired heater, reactor or furnace, or any conventional heat exchanger device, wherein all these devices are viewed as heat-consuming units 101. In still further configurations, the fluid, such as gas, heated in the rotary apparatus 100 does not necessarily transfer its thermal energy to the heat-consuming unit 101, but the heat is used to run endothermic reactions within same or subsequent rotary apparatus unit(s) 100.

In some configurations, a number of rotary apparatuses 100 can be connected to several heat-consuming units 101 (e.g. reactors for hydrogen production). Different configurations may be conceived, such as *n*+x rotary apparatuses connected to *n* units 101, wherein *n* is equal to or more than zero (0) and x is equal to or more than one (1). Thus, in some configurations, the facility 1000 may comprise one, two, three or four parallel rotary apparatuses 100 connected to the common heat-consuming unit 101; the number of rotary apparatuses exceeding four (4) is not excluded.

In embodiment, an amount of input energy E_1 is conducted into the at least one rotary apparatus 100 integrated, as a (rotary) heater unit, into the heat-consuming process facility 1000. The input energy E_1 preferably comprises electrical energy. In embodiments, the amount of electrical energy conducted as the input energy into the at least one rotary apparatus integrated in the heat-consuming process facility is provided within a range of about 5 to about 100 percent, preferably, within a range of about 50 to about 100 percent. Thus, the amount of electrical energy conducted as the input energy into the at least one rotary apparatus integrated in the heat-consuming process facility can constitute any one of: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, and 100 percent (from the total energy input), or any intermediate value falling in between the above indicated points.

Electrical energy can be supplied from external or internal source. In practice, electrical input energy *E1* supplied into the apparatus can be defined in terms of electric power, the latter being defined as a rate of energy transfer per unit time (measured in Watt).

Particulars of some embodiments of the invention, as implemented in the facility layout of Figure 1, are described along the following lines. The following designations are used for the members.

Streams: **1**. Feed; **2**. Preheated feed or feed mixture; **3**. Feed heated by virtue of a rotary apparatus 100; **4**. Feed further heated in an additional (booster) heater unit configured to raise/enhance temperature through (exothermic) chemical reactions, for example; **5**. Hot fluidic medium exiting the heat-consuming process 101; **6**. Fluidic medium directed to purification; **7**. Product stream and/or waste gas; **8**. Reactive compound or a mixture of compounds, e.g. reactive chemical(s) or a support fuel used to increase temperature of the fluid/gas in the additional heater unit 103; **9**. Process stream (solid, liquid, gas, vapor or a mixture thereof) to be heated by the hot fluidic medium in the heat-consuming process 101 (indirect heater applications); **10**. Heated process stream (solid, liquid, gas, vapor or a mixture thereof) sent for further processing and/or storage (indirect heater applications); **11**. Recycle stream exiting from purification; **12**. Feed stream to heat recovery; **13**. Hot fluidic stream from heat recovery.

Sections (units): **100**. Rotary heater unit (rotary apparatus(es)); **101**. Heat-consuming operational (process) unit; **102**. Preheater unit; **103**. Additional heating apparatus (booster heater); **104**. Heat recovery unit; **105**. Purification unit.

The rotary apparatus 100 is configured to receive a feed stream 1, hereafter, a feed. Overall, the feed 1 can comprise or consist of any suitable fluid, such as liquid or gas or a combination thereof, provided as a pure component or a mixture of components. The feed can be a feedstock liquid or gas, such as methane, natural gas, a mixture of methane and natural gas, shale gas, refinery off-gas, liquefied petroleum gas, naphtha or any other suitable hydrocarbon-containing feedstock, a process gas/working gas, a make-up gas (a so-called replacement / supplement gas), a recycle gas, and the like. Gaseous feed can include inert gases (steam, air, nitrogen gas, and the like) or reactive gases (e.g. oxygen), flammable gases, such as hydrocarbons, or any other gas. Selection of the feed is process dependent. Hence, the nature of the heat-consuming process 101 and, indeed, a specific industry / an area of industry said heat-consuming process 101 is assigned to implies certain requirements and/or limitations on the selection of feed substance(s). Additionally or alternatively, feed 1 may include any one of: (water) steam, nitrogen (N_2), hydrogen (H_2), carbon dioxide (CO_2), and carbon monoxide (CO).

It is preferred that feed 1 enters the apparatus 100 in essentially gaseous form. Preheating of feed or conversion of liquid or essentially liquid feed(s) into gaseous form can be performed in an optional preheater unit 102 configured as a (pre)heater apparatus or a group of apparatuses. In the preheater unit 102, the feed stream(s) originally provided in gaseous form (e.g. the process gas or gases) can be further heated (e.g. superheated). In the preheater unit 102, the feed 1 can be vaporized if not already in gas form and optionally superheated.

The preheater unit 102 can be any conventional device/system configured to provide heat to the fluidic substance. In some configurations, the preheater unit 102 can be a fired heater (viz. a direct-fired heat exchanger that uses hot combustion gases (flue gases) to raise the temperature of a fluidic feed flowing through the coils arranged inside the heater). Additionally or alternatively, the preheater unit 102 can be configured to exploit energy made available by the other units in the heat-consuming facility (for example by extracting thermal energy from hot stream 13 arriving from heat recovery). The preheater unit 102 can thus be configured to utilize other steam streams, as well as electricity and/or e.g. waste heat streams (not shown).

Depending on a hydrogen production related heat-consuming process and equipment, the feed stream 1 used to produce the heated fluidic medium by virtue of the rotary heater unit (the apparatus 100) may comprise a virgin feed (fresh feed) and/or recycle stream(s). Hence, the feed 1 may consist of any one of fresh feed, recycle (fluidic) stream, and a mixture thereof.

Stream 2 representing (pre)heated feed may include, in addition to feed 1, all recycle streams, such as those arriving from a purification section 105 and/or a heat recovery section 104.

In the rotary heater unit / the rotary apparatus 100, the temperature is raised to a level which is required by the heat-consuming process 101 or to a maximum level achieved by the rotary apparatus. In an event the temperature rise achieved by the rotary apparatus 100 is not sufficient for the heat-consuming process and/or if, for example, the temperature of the fluid needs to be raised again after it has transferred its heat to the heat-consuming process, further temperature rise can be achieved by virtue of arranging additional heater units (100B, 103), further referred to as "booster" heater(s), downstream of the rotary heater unit 100 (100A); rf. description to Fig. 2B. Each additional heater unit comprises or consists of an additional heating apparatus implemented according to the description below.

In heat-consuming processes associated with production of hydrogen, the main sources of heat consumption are heating of working fluids and/or associated equipment and endothermic reactions (reactions that require external energy to proceed). In some applications it is feasible to recover heat from heat-consuming processes 101. Heat recovery section is indicated on Fig. 1 with ref. no. 104. Recovered heat can be further used for heating the feed stream 1 and/or a recycle stream (separate recycle stream is indicated on Fig. 1 with ref. no. 11).

Heat recovery may be arranged through collecting gases exiting the process unit 101 and recycling these gases to the preheater unit 102 and/or the rotary apparatus 100. The heat recovery installation 104 may be represented with at least one heat exchanger device (not shown). Heat exchangers based on any appropriate technology can be utilized. Heat recovery may be optional for heating feed gas if the heat is consumed elsewhere or if it is not possible to recover heat due to safety- or any other reason.

In the facility layout 1000, the heat recovery unit 104 can be arranged before and/or after the preheater 102. In the latter configuration, the heat recovery unit 104 is arranged to recover heat from the hot fluidic medium (stream 5) flowing from the hydrogen production process 101, which may be further utilized to heat the feed stream 1 and recycle stream 11. On the other hand, when the heat recovery unit 104 is arranged before the preheater 102, the feed 1 is first led to the unit 104 (as stream 12) and then returned to preheating 102 as stream 13. In such a case, unit 104 acts as a first preheater.

In some instances, gases require purification, e.g. from dust and fine particles, before being directed to heat recovery. Purification can be done by a series of filters, for example, arranged before the heat recovery section 104 (not shown). Additionally or alternatively the gases exiting

the process unit 101 may be directed to a purification unit 105 (bypassing the unit 104), and, after purification, returned to the heat recovery (not shown).

Process gas may contain in addition to value products also unwanted impurities and side products which may accumulate and/or be harmful for heater apparatus(-es) 100, 103 and/or the process units 101 through causing corrosion and poisoning catalytic beds. Purification and separation of streams discharged from heat-consuming processes 101 is performed in the purification unit 105. Unit 105 can comprise a number of appliances, such as filters, cyclones etc., adapted to mechanically remove dust and solid particles. Any conventional purification / separation methods and devices may be utilized. Exemplary purification / separation methods include, but are not limited to: cryogenic separation methods, membrane processes, Pressure Swing Adsorption (PSA), distillation, absorption, and any combination of these methods. The unit 105 may also comprise device configured to increase gas pressure by compression, for example. Typically, purification units 105 operate at lower temperatures than the process units 101; therefore, prior to entering the purification unit, a product gas stream is cooled down (in the heat recovery 104, for example). To minimize the extent of deterioration of reactor beds in 101, it is also important to control composition of the recycle gas 11.

Purification unit 105 can be further adapted to purify waste gas(es), e.g. carbon dioxide, for further carbon capture. Waste gases discharged from the hydrogen production facility as stream 7 (Fig. 1) can thus be further directed to carbon capture (not shown). Suitable methods for purification of waste gases include for example PSA, distillation, absorption, etc.

Heated fluidic medium required for carrying out the heat-consuming process(es) 101 is generated by virtue of at least one rotary apparatus 100.

In an embodiment, the heated fluidic medium is generated in the rotary apparatus 100, where an amount of thermal energy is added directly into fluidic medium propagated through said apparatus. In such an event, the heated fluidic medium generated in the rotary apparatus may be for example a process gas, such as a hydrocarbon-containing gas (e.g. methane-containing feed gas, natural gas, or a mixture thereof) (see Fig. 1, streams 1-4, particularly stream 2), while the hot fluidic medium 5 that exits the heat-consuming unit 101 may represent a product-containing stream, such as hydrogen-containing stream. In direct heating, streams 1-5 relate to a working- or process fluid.

The heated fluidic medium generated in the rotary apparatus can be further used as a carrier to transfer thermal energy to the heat-consuming unit/process 101, configured to implement or mediate conversion of hydrocarbon-containing feed, such as for example methane-containing feed, to hydrogen. For example, an inert gas such as air, nitrogen or steam (H_2O) can be heated

in the rotary apparatus 100 and further used to convey the heat generated by the rotary apparatus to a reactor or furnace adapted to perform the hydrogen production process 101. In this regard, generation of a heated medium (e.g. fluidic streams exploited by the process 101) can be performed outside the rotary apparatus through a process of heat transfer between the heated fluidic medium generated in the rotary apparatus and a suitable medium exploited by the process 101 and thus bypassing the rotary apparatus. In the process or processes related to hydrogen production, generation of the heated hydrocarbon-containing (feed) gas (e.g. methane) outside the rotary apparatus is implemented through a process of heat transfer between the heated fluidic medium other than the hydrocarbon-containing (feed) gas generated in the rotary apparatus (e.g. steam, air, nitrogen, etc.) and a stream of hydrocarbon -containing (feed) gas bypassing the rotary apparatus. Fig. 1 thus shows stream 9 (a process stream) bypassing the rotary apparatus 100 and designating, in present context, the hydrocarbon-containing feed/process stream, while streams 1-4 arriving to the process unit 101 via the rotary heater 100 designate fluidic medium (e.g. steam or other inert heating media) directed to the process unit 101 for heating the "cold" process stream 9. Use of inert hot gases as heating media in indirect heating applications is preferred when the process fluids to be heated (e.g. methane or natural gas) are at high pressure or under vacuum. Stream 10 represents a "hot" process stream, respectively. In an event the unit 101 is a methane conversion unit, stream 10 represents the product (hydrogen)-containing stream, and stream 5 represents, in turn, a stream of inert fluidic medium (same as 1-4) exiting the unit/process 101. In indirect heating, streams 9 and 10 relate to a working- or process fluid, whereas streams 1-5 represent a heat-transfer medium. Hence, in indirect heating, the unit 101 acts as a "heat-exchanger" type of device which enables transfer of thermal energy between two fluids flowing therethrough without any direct contact between said fluids.

Exemplary processes of steam methane reforming employing the apparatus 100 for direct heating of process fluids are presented on Figs. 4A and 4B, and for indirect heating of process fluids – on Fig. 4C, respectively.

The rotary apparatus 100 configured for generating the heated fluidic medium to be supplied into the hydrogen production facility according to the embodiments comprises a rotor comprising a plurality of rotor blades arranged into at least one row over a circumference of a rotor hub or a rotor disk mounted onto a rotor shaft, and a casing with at least one inlet and at least one exit, the rotor being enclosed within the casing. In the apparatus 100, an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the at least one row of rotor blades

when propagating inside the casing of the rotary apparatus, between the inlet and the exit, whereby a stream of heated fluidic medium is generated.

Implementation of the rotary apparatus 100 may generally follow the disclosures of a rotary reactor apparatus according to the U.S. patents nos. 7,232,937 (Bushuev), -9,494,038 (Bushuev) and no. 9,234,140 (Seppälä et al), and of a radial reactor apparatus according to the U.S. patent no. 10,744,480 (Xu & Rosic), the entire contents of which are incorporated by reference herewith. Any other implementation, which can be configured to adopt the method according to the embodiments, can be utilized.

In the patent documents referenced above, the rotary turbomachine-type apparatuses were designed as reactors for processing hydrocarbons, in particular, for steam cracking. General requirements for these applications are: rapid heating of gases, high temperature, short residence time, and plug flow (a flow model which implies no axial mixing). These requirements have led to designs where the turbomachine type reactors have several heating stages accommodated in a relatively small volume.

The present disclosure is based on an observation that the rotary apparatus (including, but not limited to the ones referenced above) can be electrified and used as a heater to generate the heated fluidic medium further supplied in the heat-consuming process 101, such as a process or processes related to production of hydrogen. By integration of the rotary apparatus heater unit(s) into the heat-consuming process or processes, significant reductions in greenhouse gas- and particle emissions can be achieved. By way of example, the rotary apparatus can replace fuel-fired heaters in steam methane reforming processes described hereinbelow. The temperature range can be extended from about 1000 °C (generally achievable with the above referenced reactor devices) to up to at least about 1700 °C and further up to 2500 °C. Construction of the rotary apparatuses capable of achieving these high temperatures is possible due to an absence of aerodynamic hurdles.

The rotary apparatus 100 integrated into the hydrogen production facility according to the embodiments and configured to generate the heated fluidic medium for the method(s) according to the embodiment thus comprises the rotor shaft positioned along a horizontal (longitudinal) axis with at least one rotor unit mounted onto the rotor shaft. The rotor unit comprises a plurality of rotor (working) blades arranged over the circumference of a rotor hub or a rotor disk and together forming a rotor blade cascade. The rotary apparatus 100 thus comprises a plurality of rotor (working) blades arranged into at least one row over the circumference of a rotor hub or a rotor disk mounted onto the rotor shaft, and forming an essentially annular rotor blade assembly or rotor blade cascade.

In embodiments, the apparatus further comprises a plurality of stationary vanes arranged into an assembly disposed at least upstream of the at least one row of rotor blades. In this configuration, the rotary apparatus is operated such that the amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary vanes and the at least one row of rotor blades, respectively, whereby a stream of heated fluidic medium is generated.

In some embodiments, the plurality of stationary vanes can be arranged into a stationary vane cascade (a stator), provided as an essentially annular assembly upstream of the at least one row of rotor blades. The stationary vanes arranged into the assembly disposed upstream of the at least one row of rotor blades may be provided as stationary guide vanes, such as (inlet) guiding vanes (IGV), and be configured, in terms of profiles, dimensions and disposition thereof around the central shaft, to direct the fluid flow into the rotor in a predetermined direction such, as to control and, in some instances, to maximize the rotor-specific work input capability.

The rotary apparatus can be configured with two or more essentially annular rows of rotor blades (rotor blade cascades) sequentially arranged on/along the rotor shaft. In such an event, the stationary guide vanes may be installed upstream of the first row of the rotor blades, upstream of each row of rotor blades in the sequence, or upstream of any selected row of rotor blades in a sequential arrangement of the latter.

In embodiments, the rotary apparatus 100 further comprises a diffuser area arranged downstream of the at least one row of rotor blades (rotor blade cascade). In this configuration, the rotary apparatus is operated such that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium successively passes through the stationary guide vanes, the at least one row of rotor blades and the diffuser area, respectively, whereby a stream of heated fluidic medium is generated. The diffuser area can be configured with or without stationary diffuser vanes. In some configurations, a vaned or vaneless diffuser is arranged, in said diffuser area, downstream of the at least one rotor blade cascade. In some configurations, the diffuser can be implemented as a plurality of stationary (stator) vanes arranged into a diffuser vane cascade, provided as an essentially annular assembly downstream of the rotor.

The rotor, the stationary guide vanes and the diffuser area are enclosed within an internal passageway (a duct) formed in the casing.

In some configurations, such as described for example in US 10,744,480 to Xu and Rosic, provision of a diffuser (device) may be omitted, and the diffuser area may be represented with an essentially vaneless portion of the duct (a so-called vaneless space) located downstream of the rotor and configured, in terms of its geometry and/or dimensional parameters, to diffuse a high-speed fluid flow arriving from the rotor.

Provision of the vaneless portion of the duct is common for all configurations of the rotary apparatus 100 described above. Depending on configuration, the vaneless portion (vaneless space) is arranged downstream of the rotor blades (rf. US 10,744,480 to Xu and Rosic) or downstream of the diffuser vane cascade (rf. U.S. 9,494,038 to Bushuev and U.S. 9,234,140 to Seppälä et al). In some configuration described for example by Seppälä et al, arrangement of rotating and stationary blade rows in the internal passageway within the casing is such that vaneless portion(s) is/are created between an exit from the stationary diffuser vanes disposed downstream of the rotor blades and an entrance to the stationary guide blades disposed upstream of the rotor blades of a subsequent rotor blade cascade unit.

The terms "upstream" and "downstream" refer hereby to spatial and/or functional arrangement of structural parts or components with relation to a predetermined part- or component, hereby, the rotor, in a direction of fluidic flow stream throughout the apparatus (from inlet to exit).

Overall, the rotor with the working blade cascade can be positioned between the rows of stationary (stator) vanes arranged into essentially annular assemblies (referred to as cascades) at one or both sides of the working blade row. Configurations including two or more rows of rotor blades /rotor blade cascades arranged in series (in sequence) on/along the rotor shaft may be conceived with or without stationary blades in between. In an absence of stationary vanes between the rotor blade rows, the speed of fluidic medium propagating through the duct increases in each subsequent row. In such an event, a plurality of stationary vanes may be arranged into assemblies upstream of a first rotor blade cascade in said sequence (as stationary guide vanes) and downstream of a lastmost rotor blade cascade (as stationary diffuser vanes).

The row of rotor blades (rotor blade cascade) and a portion of the duct downstream of said rotor blades enclosed inside the casing optionally provided with an assembly of stationary diffuser vanes (diffuser area) may be viewed as a minimal process stage (hereafter, the stage), configured to mediate a complete energy conversion cycle. Hence, an amount of kinetic energy added to the stream of fluidic medium by at least one row of rotating blades is sufficient to raise the temperature of the fluidic medium to a predetermined value when said stream of fluidic medium exits the rotor blades and propagates, in the duct, towards a subsequent row of rotor blades, or enters the same row of rotor blades following an essentially helical trajectory formed

within the essentially toroidal-shaped casing. The duct (which encloses the periphery of the rotor) is preferably shaped such, that upon propagation of the fluidic stream in the duct, the stream decelerates and dissipates kinetic energy into an internal energy of the fluidic medium, and an amount of thermal energy is added to the stream of fluidic medium.

The stationary guide blade row(s) disposed upstream of the at least one row of rotor blades prepare required flow conditions at the entrance of the rotating blade row (cascade) during the energy conversion cycle.

In some configurations, the process stage is established with the assembly of stationary guide vanes (upstream of the rotor blades), the row of rotor blades and the diffuser area arranged downstream of said rotor blades, the diffuser area provided as the essentially vaneless portion of the duct optionally supplied with diffuser vanes. During the energy conversion cycle, enabled with successive propagation of the stream of fluidic medium through the stationary guide vanes, the at least one row of rotor blades and the diffuser area, respectively, in a controlled manner, mechanical energy of the rotor shaft is converted into kinetic energy and further – into internal energy of the fluid, followed by the rise of fluid temperature. An amount of kinetic energy added to the stream of fluidic medium by rotating blades of the rotor is sufficient to raise the temperature of the fluidic medium to a predetermined value when said stream of fluidic medium exits the rotor blades and passes, inside the duct, through the diffuser area, whereupon the stream decelerates and dissipates kinetic energy into an internal energy of the fluidic medium, and an amount of thermal energy is added to the stream of fluidic medium. In the rotor blade row, the flow accelerates, and mechanical energy of the shaft and rotating blades is transferred to fluidic stream. In at least part of each rotor blade row the flow may reach a supersonic flow condition. In the diffuser area, the high-speed fluid flow arriving from the rotor is diffused with the significant entropy increase, whereby the flow dissipates kinetic energy into the internal energy of the fluidic substance, thus providing thermal energy into the fluid. If the flow upstream of the diffuser is supersonic, the kinetic energy of the fluidic stream is converted into internal energy of the fluid through a system of multiple shocks and viscous mixing and dissipation. An increase in the internal energy of the fluid results in a rise of fluid temperature. The energy conversion function may be performed by the vaneless portion of the duct located downstream of the rotor blades (rf. U.S. 10,744,480 to Xu & Rosic) and/or by an assembly of diffusing vanes, for example (rf. U.S. 9,234,140 to Seppälä et al).

The rotary apparatus 100 can be configured as a multistage- or a single-stage solution. Multistage configurations can be conceived comprising a number of rotor units (e.g. 1-5 rows of rotor blades sequentially arranged on/along the rotor shaft) alternating with common diffuser area(s) (vaneless or vaned).

Integration of the rotary apparatus 100 into high-temperature processes related to hydrogen production allows for avoiding or at least greatly reducing formation of carbon deposits on hot heating surfaces in furnaces or other type of heaters due to long residence time. Residence time of feedstock gas, such as for example methane, in the rotary apparatus can be minimized such that an extent of carbon formation will be decreased significantly. Additionally or alternatively, the temperature of a feedstock gas propagating through the rotary apparatus can be increased to a level at which reactions proceed with sufficiently high conversion rates and essentially in an absence of carbon deposits. This can be achieved by providing, within the interior of said apparatus, a single rotor unit or a number of rotor units arranged in series before the diffuser area.

In an exemplary configuration outlined in U.S. 9,234,140 to Seppälä et al, the rotary apparatus 100 can be implemented substantially in a shape of a ring torus, where a cross-section of the duct in the meridian plane forms a ring-shaped profile. The apparatus comprises a rotor unit disposed between stationary guide vanes (nozzle vanes), and stationary diffusing vanes. The stages are formed with rows of stationary nozzle vanes, rotor blades and diffusing vanes, through which the fluidic stream propagates, in a successive manner, following a flow path established in accordance with an essentially helical trajectory. In this configuration, fluidic stream circulates through the rotating rotor blade cascade a number of times while propagating inside the apparatus between the inlet and the exit. Similar ring-shaped configuration is described in U.S. 9,494,038 to Bushuev.

In another exemplary configuration outlined in U.S. 9,234,140 to Seppälä et al, the rotary apparatus 100 can be configured as an essentially tubular, axial-type turbomachine. In such configuration, the apparatus comprises an extended (elongated) rotor hub, along which a plurality of rotor blades is arranged into a number of sequential rows. The rotor is enclosed within the casing, inner surface of which is provided with the stationary (stator) vanes and diffuser vanes, arranged such that blades/vanes of the stator, rotor- and diffuser cascades alternate along the rotor hub in a longitudinal direction (along the length of the rotor shaft, for inlet to exit). Blades of the rotor cascade at certain position along the rotor in the longitudinal direction form the stage with the adjacent pairs of stationary guide (nozzle) vanes and diffusing vanes, respectively.

In described configurations, the subsequent stages have blade/vane-free space between them.

In still another exemplary configuration outlined in US 10,744,480 to Xu and Rosic, the rotary apparatus 100 can be configured as a radial turbomachine that generally follows a design for centrifugal compressors or centrifugal pumps. The term “centrifugal” implies that fluid flow

within the device is radial; therefore, the apparatus may be referred, in the present disclosure, as a "radial-flow apparatus. The apparatus comprises a number of rotor units mounted onto elongated shaft, wherein each rotor unit is preceded with stationary guide vanes. A vaneless portion of the duct shaped in a manner enabling energy conversion (U-bend or S-bend, for example) is located after the rotor unit(s). Additionally, configuration may comprise a separate diffuser device (vaned or vaneless) disposed downstream of the rotor.

In all configurations described above, the rotary apparatus 100 performs, in the method disclosed herein, in similar manner. In operation, the amount of input energy conducted into the at least one rotary apparatus integrated into the heat-consuming process facility is converted into mechanical energy of the rotor. Conditions in the rotary apparatus are adjusted such, as to produce flow rate conditions, at which an amount of kinetic energy added to the stream of fluidic medium by rotating blades of the rotor is sufficient to raise the temperature of the fluidic medium to a predetermined value when said stream of fluidic medium exits the at least one row rotor blades and passes through the duct and/or through the diffuser area to enter the subsequent row of rotor blades or the same row of rotor blades in accordance to the description above. The row(s) of rotor blades may be preceded with stationary guide vanes. Hence, the adjustable condition comprises adjusting at least a flow of fluidic medium propagating inside the casing of the rotary apparatus, between the inlet and the exit. Adjusting the flow may include adjusting such apparatus operation related parameters, as temperature, mass flow rate, pressure, etc. Additionally or alternatively, flow conditions can be adjusted by modifying shape of the duct formed inside the casing.

In some exemplary configurations, the rotary apparatus can be configured to implement a fluidic flow between its inlet(s) and outlet(s) along a flow path established in accordance with any one of: an essentially helical trajectory formed within an essentially toroidal-shaped casing, as discussed in any one of the patent documents U.S. 9,494,038 to Bushuev and U.S. 9,234,140 to Seppälä et al; an essentially helical trajectory formed within an essentially tubular casing, as discussed in the patent document U.S. 9,234,140 to Seppälä et al; an essentially radial trajectory as discussed in the patent document U.S. 10,744,480 to Xu & Rosic; and along the flow path established by virtue of the stream of fluidic medium in the form of two spirals rolled up into vortex rings of right and left directions, as discussed in the patent document U.S. 7,232,937 to Bushuev). The aerodynamic design of the rotary apparatus can vary.

The rotary apparatus utilizes a drive engine. In preferred embodiments, the apparatus utilizes electrical energy as the input energy and is therefore electric motor-driven. For the purposes of the present disclosure, any appropriate type of electric motor (i.e. a device capable of transferring energy from an electrical source to a mechanical load) can be utilized. Suitable

coupling(s) arranged between a motor drive shaft and the rotor shaft, as well as various appliances, such as power converters, controllers and the like, are not described herewith. Additionally, the apparatus can be directly driven by gas- or steam turbine, for example, or any other appropriate drive device. In layouts involving parallel connection of a number of rotary apparatuses 100 to the common heat-consuming unit 101, one or more of said apparatuses may utilize different type of drive engine, e.g. the electric motor driven apparatuses can be combined with those driven by steam turbine, gas turbine and/or gas engine.

Electric power (defined as the rate of energy transfer per unit time) can be supplied into the rotary apparatus through supplying electric current to the electric motor used to propel a rotary shaft of the apparatus. Supply of electric power into the rotary apparatus can be implemented from an external source or sources (as related to the rotary heater unit / the apparatus 100 and/or the heat-consuming process facility 1000). Additionally or alternatively, electrical energy can be produced internally, within the facility 1000.

An external source or sources include a variety of supporting facilities rendered for sustainable energy production. Thus, electric power can be supplied from an electricity generating system that exploits at least one source of renewable energy or a combination of the electricity generating systems exploiting different sources of renewable energy. External sources of renewable energy can be provided as solar, wind- and/or hydropower. Thus, electric power may be received into the process from at least one of the following units: a photovoltaic electricity generating system, a wind-powered electricity generating system, and a hydroelectric power system. In some exemplary instances, a nuclear power plant may be provided as the external source of electrical power. Nuclear power plants are generally regarded as emission-free. The term “nuclear power plant” should be interpreted as using traditional nuclear power and, additionally or alternatively, fusion power.

Electricity can be supplied from a power plant that utilizes a turbine as a kinetic energy source to drive electricity generators. In some instances, electric power to drive the at least one apparatus 100 can be supplied from at least one gas turbine (GT) provided as a separate installation or within a cogeneration facility and/or a combined cycle power facility, for example. Electric power can thus be supplied from at least one of the following units: a combined cycle power facility, such as a combined cycle gas turbine plant (CCGT), and/or a cogeneration facility configured for electricity production combined with heat recovery and utilization through combined heat and power (CHP), for example. In some examples, the CHP plant can be a biomass fired plant to increase the share of renewable energy in the process described. Additionally or alternatively, supply of electric power can be realized from a spark ignition engine, such as a gas engine, for example, and/or a compression engine, such as a diesel

engine, for example, optionally provided as a part of an engine power plant. Still further, any conventional power plant configured to produce electrical energy from fossil raw materials, such as coal, oil, natural gas, gasoline, and the like, typically mediated with the use of steam turbines, can be used to generate electrical energy as an input energy for the rotary apparatus 100. Also hydrogen can be utilized as a source of renewable energy, to be reconverted into electricity, for example, using fuel cells.

Any combination of the abovementioned sources of electric power, realized as external and internal sources, may be conceived. Importing low emission electric power from an alternative (external) source improves energy efficiency of the heat-consuming process facility.

Conducting input energy, comprising electrical power, into a drive engine of the rotary apparatus can be further accompanied with conducting mechanical shaft power thereto from a power turbine, for example, optionally utilizing thermal energy generated elsewhere in the facility 1000 or outside said facility. Shaft power is defined as mechanical power transmitted from one rotating element to another and calculated as a sum of the torque and the speed of rotation of the shaft. Mechanical power is defined, in turn, as an amount of work or energy per unit time (measured in Watt).

In practice, the shaft power from the electric motor and the power turbine, for example, can be divided so that any one of those can provide the full shaft power or a fraction of it.

Figs. 2A-2D show exemplary layouts for the rotary apparatus 100 representing the rotary heater unit or units within the facility 1000 with regard to preheater unit 102, temperature booster section 103, and heat recovery unit 104. The following citations are used for the members: 100, 100A, 100B – Rotary heater unit(s) (rotary apparatus(es)); 101 – Heat-consuming unit/process; 102 – Preheater unit; 103 – Additional heating apparatus (booster heater).

Fig. 2A schematically illustrates a basic implementation for the rotary apparatus 100 configured to input heat into a stream of fluidic medium (feed stream 1) directed therethrough. Heated stream exiting the apparatus 100 is designated with reference number 2, respectively. In basic implementation, the rotor system of the rotary apparatus 100 is aerodynamically configured so that a volume of fluid is heated to a predetermined temperature while propagating along the flow path formed in the casing of the apparatus 100, between inlet and exit (so called "one-pass" implementation). The apparatus 100 enables temperature rise (delta T, ΔT) within a range of about 10 °C to about 120 °C, in some configurations – up to about 500 °C, in one stage. Hence, in case of a multistage implementation, the fluid can be heated to 1000 °C in "one-pass" implementation (taken 100 °C temperature rise per stage in a 10-stage apparatus). Since residence time the fluidic medium spends to pass through the apparatus stage is in scale of

fractions of seconds, such as about 0,01-1,0 milliseconds, fast and efficient heating can be achieved already in the basic configuration. Temperature rise can be optimized as required.

Fig. 2B illustrates a basic concept involving so-called booster heating. Booster heating is an optional method to heat a fluidic medium, such as a process gas, for example, beyond capability of a standalone heater apparatus 100.

Temperature boost may be viewed as thermal, chemical or both. In a first configuration (a) also referred to as a "thermal boost", an additional rotary heater apparatus (designated as 100B on Figs. 2B, 2C and 2D) is arranged downstream of a "primary" rotary heater apparatus (designated as 100A on Figs. 2B, 2C and 2D). Apparatuses 100A, 100B are generally recognized, within the present disclosure, as rotary heater units 100. Generation of the heated fluidic medium is can thus be achieved by provision of at least two sequentially connected rotary apparatuses 100A, 100B, wherein the stream of fluidic medium (rf. feed stream 1) is heated to a predetermined temperature in at least a first rotary apparatus (100A) in a sequence, referred to hereby as a primary heater, and wherein said stream of fluidic medium (rf. stream 2) is further heated in at least a second rotary apparatus (100B) in the sequence by inputting an additional amount of thermal energy into the stream of fluidic medium "preheated" in the first rotary apparatus 100A and propagating through the second rotary apparatus 100B (rf. stream 3). The apparatus 100B is therefore referred to as a booster heater. The apparatuses 100A, 100B may be identical and vary in terms of size or internal design. A sequence of two or more booster apparatuses such as 100B can be arranged after a primary heater 100A. Booster apparatuses can be arranged in parallel or in series, or in any combination that allows for optimization of rotating speed and aerodynamics thereof.

In a second, additional or alternative, configuration (further referred to as "chemical boost"), the additional heating apparatus designated as 103 (Figs. 1, 2B) is adapted to receive, into the stream of fluidic medium propagating therethrough, reactive components 5, such as for example combustible fuel, to provide heat by exothermic reactions prior to directing said stream of fluidic medium to the heat-consuming process 101 of hydrogen production. In this configuration, temperature boosting can be achieved by virtue of introducing (e.g. by injecting) a reactive chemical or chemicals 5 into to the stream of fluidic medium directed through the additional heater unit/heating apparatus 103. It is noted that stream 5 of Fig. 2B corresponds to stream 8 shown on Fig. 1.

The reactive chemical-based booster heater unit 103 may be located after the thermal booster heater unit 100, 100B (Fig. 2B) or directly after the primary heater 100, 100A (Fig. 1). The reactive chemical (reactant) 5 may include combustion gases, such as hydrogen gas,

hydrocarbons, ammonia, oxygen, air, other gas and/or any other appropriate reactive compound, optionally a catalyst. In the unit 103, by virtue of exothermic reactions, the fluidic stream can be heated to a level, which is typically not possible to achieve by a single rotary apparatus not involving chemical-mediated heating (rf. stream 4). For example, a fuel gas, such as hydrogen, can be introduced into an oxygen-containing process gas, such as air. At elevated temperatures, hydrogen and oxygen enter an exothermic reaction to produce water molecules (hydrogen combustion).

Fuel gas can be injected into the booster heater unit 103 through burners along with air (or enriched oxygen) to rise the temperature of gases. If heated gas contains flammable gases and it is possible to consume these gases for heating only air/or oxygen can be added. Process gases can contain H_2, NH_3, CO, fuel gases (methane, propane, etc.) which may be burned to generate heat. Other reactive gases can be injected to generate heat if feasible.

The additional heater 103 adapted for chemical boost may be configured as a piece of pipe or as a chamber where exothermic reactions take place, and/or it can comprise as at least one rotary apparatus 100 arranged to receive reactive compounds to accommodate exothermic reactions to produce additional heat energy. The booster section 103 can thus comprise at least one rotary apparatus 100. Optionally, the reactive chemicals can be injected directly to the heat consuming process 101 (not shown). Additionally or alternatively, the reactive chemical mediated boost can be implemented in a single apparatus 100, 103, modified accordingly.

In an arrangement involving booster heating, the temperature of the stream of fluidic medium preheated to a predetermined temperature in a first rotary apparatus (100A) can be further raised to a maximum limit in subsequent heater units (100B, 103). By way of example, the temperature of the stream of fluidic medium preheated to about 1700 °C in a primary heater (100A) can be further raised in subsequent heater units (100B, 103) up to 2500 °C and beyond.

Mentioned concepts can be used separately or in combination, so that the reactive chemical 5 can be introduced into any one of the apparatuses 100 connected in parallel or in series (in sequence). Provision of the booster heater(s) is optional.

In additional or alternative configurations, preheating and additional heating can be implemented in the same apparatus 100 (not shown). This can be achieved in multistage configurations, comprising a number of rotor units (e.g. 1-5 rows of rotor blades sequentially arranged on/along the rotor shaft) alternating with common diffuser area(s) (vaneless or vaned).

Additionally or alternatively, booster heating can be used for example in an event, when the temperature of the fluid once heated in the rotary apparatus(es) 100, needs to be raised again

after it has transferred its heat to the heat-consuming process 101. Exemplary configuration comprising a number of rotary heater apparatuses 100 (100A, 100B and/or optionally 103) alternating with the heat-consuming units 101 is shown on Fig. 2E. Such configuration can be utilized for example for a series of successive catalytic endothermic reactors, where the temperature drops reactor-wise and needs to be raised again between the reactors (see description to Fig. 5A).

Upon connecting the at least two rotary apparatuses, such as 100A, 100B, and optionally 103 (in an event 103 is implemented as a rotary apparatus 100) in parallel or in series, a rotary apparatus assembly can be established (see for example Figs. 2B-2D). Connection between the rotary apparatuses 100 implemented as "primary" heater(s) 100A or "booster" heater(s) 100B, 103 can be mechanical and/or functional. Functional (in terms of achievable heat input, for example) connection can be established upon association between at least two individual, physically integrated- or non-integrated individual apparatus units. In a latter case, association between the at least two rotary apparatuses can be established via a number of auxiliary installations (not shown). In some configurations, the assembly comprises the at least two apparatuses connected such, as to mirror each other, whereby said at least two apparatuses are at least functionally connected via their central (rotor) shafts. Such mirrored configuration can be further defined as having the at least two rotary apparatuses 100 mechanically connected in series (in a sequence), whereas functional connection can be viewed as connection in parallel (in arrays). In some instances, the aforesaid "mirrored" arrangement can be further modified to comprise at least two inlets and a common exhaust (discharge) module placed essentially in the center of the arrangement.

Rotary apparatuses (100A, 100B, 103, rf. Fig. 2B) can be assembled on the same (rotor) shaft. Each rotary apparatus can be optionally provided with a separate drive (a motor) which allows independent optimization of the apparatuses. When two or more separate rotary apparatuses are used, construction costs (materials etc.) can be optimized in view of operation temperature and pressure.

Additionally or alternatively, at least one rotary apparatus within the assembly can be designed to increase the pressure of the fluidic stream. Hence, the at least one rotary apparatus in the assembly can be assigned with a combined heater and blower functionality.

Additionally or alternatively, a stream containing reactive- or inert gases can be fed to the rotary apparatus 100 (not shown) or to any equipment downstream of said apparatus (e.g. in the heat-consuming process section 101). Thus, the reactive gases may also be injected directly to the heat-consuming process unit 101, if the latter is configured as the heat-consuming unit, such as

a reactor. In a number of applications, a support fuel may be injected directly to the process unit 101 to generate heat and/or to take part in the reactions.

Fig. 2C illustrates the use of the rotary heater apparatuses 100A, optionally 100B with indirect process heating. The rotary apparatus 100 (100A, 100B) can be used for indirect heating of fluids in the heat-consuming unit 101, wherein heat is transferred between two non-mixing fluids as in heat exchanger-type configurations. Hence, fluids, such as gases or liquids, can be evaporated (vaporized) or superheated in a feasible heat exchanger arrangement 101 against fluid heated in the rotary apparatus 100. The heat-consuming unit 101 configured to accommodate a heat-consuming process can be represented with any (existing) fired heater, reactor or furnace, or any conventional heat exchanger device. Type of said "heat exchanger" configuration (101) can be selected as needed for optimal heat transfer. Heating gas (see streams 1-3) can be selected to be most suitable for heating and safety (for example: steam, N_2, air). Gas heated in the rotary apparatus 100A, 100B can be close to atmospheric pressure or pressure can be raised to improve heat transfer. Heat transfer medium 3 heated in the apparatus 100 (rf. stream 3 exiting 100B) is directed to the heat-consuming process 101, where heat is transferred from stream 3 to a "cold" process stream 6 to produce a "hot" process stream 7. Stream 4 designates the (inert) heat transfer medium outflow, respectively. In an event the unit 101 is a methane-to-hydrogen conversion unit, stream 6 will designate a methane-containing feed stream and stream 7 a hydrogen-containing product stream, respectively.

Process streams 6 and 7 of Fig. 2C thus correspond to streams 9 and 10 of Fig. 1, respectively (indirect heating configuration); while heat transfer medium streams 3 and 4 of Fig. 2C correspond to streams 3 (optionally 4) and 5, respectively (indirect heating configuration).

Another exemplary configuration layout for indirect heating of process fluids with the rotary apparatus 100 is presented on Fig. 2F. The heat-consuming unit 101 is set to act as a heat exchanger designed to heat the process stream inflow to a predetermined temperature by means of a stream of a heating medium (heat transfer medium) supplied from the rotary apparatus 100. Configuration of Fig. 2F may be applied to heating of gaseous media, such as hydrogen (gas) and/or a hydrogen-containing gas stream, in a heat exchanger 101 within the hydrogen production facility. Same layout may be applied to raise the temperature of any other process stream flowing through the heat exchanger device.

Although heating of gaseous media, such as hydrogen gas, can be implemented in the rotary apparatus 100 by simply using the steam as a heating fluid (not shown), in such cases where the pressure of hydrogen stream is elevated to above 10 bar for example or where the temperature of hydrogen stream becomes very high, for example up to above 1000 °C, it is

beneficial to apply the indirect heating concept shown on Fig. 2F. Designing the rotary apparatus to operate at high pressures and/or at high temperatures increases its material requirements and may complicate its technical solutions, which again increases an overall cost of the apparatus. However, designing the apparatus for a low-pressure heating of inert gases such as air, nitrogen, carbon dioxide or steam and using the heated gas to heat hydrogen or other process stream in the process unit 101 (in a heat exchanger configuration) can result in a lower overall cost of the heating system.

In Fig. 2F, the rotary apparatus 100 is used to heat non-working fluids (e.g. inert fluids) such as air, (water) steam, carbon dioxide or nitrogen gas (N_2) at low pressure, for example, at pressure below 10 bar. Such non-working fluid is further referred to as a "heat transfer medium". Inflow stream 4 entering the apparatus 100 (heat transfer medium, cold) has a temperature of about 200-1100 °C; and outflow stream 3 exiting 100 (heat transfer medium, hot) has a temperature of about 800-1200 °C, respectively. In turn, the temperature of "cold" process fluid 6 (for example, hydrogen) entering the heat-consuming unit 101 is about 20-500 °C, while the temperature of "hot" process fluid outflow 7 exiting 101 is about 700-1000 °C. In order to allow heat transfer from the heat transfer fluid into the process steam, the temperature of the heated fluid discharged from the rotary apparatus 100 must exceed the target temperature of the heated process fluid (e.g. hydrogen).

"Hot" fluid 3 discharged from the rotary apparatus 100 is led into the heat-consuming unit 101 provided, in the layout of Fig. 2F, as a heat exchanger that allows transfer of thermal energy from the heat transfer medium (inert fluid heated in 100) to the process fluid, such as hydrogen stream, through a heat transfer surface, resulting in heating the hydrogen stream. As the heat transfer medium donates its heat to the process stream, it cools down. Cooled heat transfer medium 4 can be reintroduced into the rotary heater apparatus 100 to improve thermal efficiency of the system.

The heat exchanger 101 materials are selected to withstand high temperature hydrogen atmosphere, and/or elevated pressures; however, for stationary equipment like heat exchangers this is still more cost-efficient option than for the rotary apparatus 100.

Using the rotary apparatus 100 allows for optimization of temperature difference in heat exchanger configurations (represented hereby by the heat-consuming units 101), whereby the size of the unit 101 (configured as a heat exchanger, a reactor, a furnace, a heater, etc.) and possible unwanted reactions (fouling, coking) occurring on its surfaces due too high surface temperature can be minimized. High surface temperatures may cause excess fouling in process

heaters. Indirect heating can be used for example to replace process heaters in various applications related to hydrogen production.

Fig. 2D illustrates the rotary heater apparatus 100A with a preheater 102 and with a recycle process fluid (stream 4) recycled from the heat consuming process (not shown). Preheater can be electric, fired, combustion engine, gas turbine, etc. or it can be a heat exchanger for recovering excess heat from any high temperature flow in the process. Provision of the preheater 102 is optional. The concept can further include an optional booster heater 100B downstream of the apparatus 100A. Stream 1' designates a (feed) fluid sent to the preheater 102. Said fluid is further propagated through the rotary apparatuses 100A, 100B, where the feed is heated and sent to the heat-consuming process at stream 3.

Any one of the rotary apparatuses 100A, 100B can be equipped with a fluid recycle arrangement (see stream 4, Fig. 2D). Any combination of the rotary apparatuses the fluid recycle arrangement can be conceived. Recycling is made possible through recirculation of the streams of fluidic medium by the at least one rotary apparatus.

In some configurations, the rotary apparatus 100 can utilize flue gases with low oxygen content exhausted from a conventional fired heater. In such an event, hot flue gases exhausted from the fired heater are mixed with recycle gases (stream 4, Fig. 2D) to be used for heating in the rotary heater 100, 100A. Oxygen content in the flue gases used in described case is preferably below a flammability limit to provide safe heating.

The method according to the aspect is applicable, fully or partly, to a variety of heat-consuming processes 101 related to production of hydrogen, as will be elucidated herein below based on a number of non-limiting examples.

Reference is made to Fig. 3, which schematically illustrates integration of the rotary apparatus 100 into a process of direct conversion of methane through methane pyrolysis, whereby hydrogen and carbon are produced. The process can be extended to produce valuable hydrocarbons, such as fuels, and/or chemicals. Except for references numbers 9 and 10, designations for the members are the same as on Fig. 1.

In the process(-es), feed 1 and/or recycle gas stream 11 (returning from the purification unit 105) undergo (pre)heating in heat recovery 104 followed with (pre)heating in the preheater 102. Alternatively, the streams 1, 11 are first heated in the preheater 102 and then in the heat recovery 104. In a process of direct conversion of methane through pyrolysis, raw feed, such as natural gas or biogas, is typically purified to an extent required for the process (not shown). Where the feed is pure methane, purification (desulphurisation etc.) is not required.

For the production of hydrogen and carbon, methane is heated (see stream 2, Fig. 3) in the at least one rotary apparatus 100, acting as a heating device, to a predetermined temperature adjusted to a level at which relevant conversion ratio can be achieved in a downstream methane conversion process 101. For thermal conversion processes, said temperature level is above 1000 C, preferably within a range of about 1300 °C to about 1700 °C. In catalytic processes, the temperature depends on selected catalyst: one of the recommended temperature values is about 800 °C, however, some catalysts operate already at about 500 °C and above. Expected residence times in the apparatus 100 are short, such as within a range of about 1-20 milliseconds. Short residence time is important to avoid coke formation in the heater (viz. in the apparatus 100). Optional additional heating apparatus 103, in which heating is mediated by injecting reactive chemicals 8 into the device 103 or upstream (see stream 3), may be arranged after the rotary apparatus 100. Additionally or alternatively, temperature boosting can be implemented with a number of rotary apparatuses 100A, 100B, optionally 103 in a rotary configuration, assembled as described hereinabove.

Methane heated to a predetermined temperature (stream 4) proceeds to the heat-consuming process /- unit 101, which can be represented with several different types of reactor devices (101A and 101B in the present example) arranged in series or parallel. Any one of the reactors 101A, 101B or both are configured to implement thermal conversion / degradation of methane to hydrogen (methane pyrolysis). In the present example, a first reactor 100A is a thermal reactor. The reactor 100A can be for example a cyclone type to allow separation of carbon by velocity and gravity. Other reactor types can be utilized. In the reactor 101A, the stream temperature may drop to a level of about 700–900°C, thereby the rate of decomposition reactions decreases. Subsequent reactor unit(s) such as 101B can comprise reactor(s) supplied with a catalyst suitable for high-temperature pyrolysis of methane and reactor(s) supplied with a different type of catalyst suitable for low-temperature pyrolysis of methane, in order to maximize conversion of methane in the reactors.

The temperature of fluid (hereby, methane gas) heated in the rotary apparatus and the residence time said fluid spends in the apparatus is adjusted below a threshold at which a heat-consuming process (hereby, pyrolysis) occurs in order to avoid initiating the heat-consuming process(es) before the fluid enters, as stream 4, a heat-consuming unit 101 (hereby, configured as a reactor for methane pyrolysis). Overall, the apparatus 100 in a typical multistage configuration is designed to raise the temperature of fluids passing therethrough in a stagewise manner. Therefore, a flow of fluidic stream propagating through the apparatus 100 can be adjusted such that a threshold temperature (temperature at which a heat-consuming process, such as methane pyrolysis in present case, occurs in the heat-consuming unit 101) is achieved at a last working stage of the apparatus – after the fluid had passed the rotor of said last working stage. In such a

way, a temperature of methane gas outflow (stream 4) discharged from the rotary apparatus 100 is approximately the temperature of methane pyrolysis. This temperature may again vary depending on presence/absence of catalyst in downstream equipment 101. Described arrangement further allows for avoiding formation of carbonaceous deposits within the rotary apparatus 100.

Stream 9 designates coke, which is removed from the thermal reactor 101A. Catalytic reactor(s) 101B may need mechanical decoking of the catalyst; therefore, stream 10 discharged from the reactor 100B may contain, along with loose carbon, also the catalyst for mechanical decoking.

Depending on the catalyst type, the temperature of stream 5 discharged from the reactor unit(s) 101B may be around 500 °C or higher. Product stream 5 comprising hydrogen is directed to the heat recovery unit 104, where hot product gas is cooled before the purification unit 105. Purification unit may consist of a hydrogen separation unit for example by pressure swing adsorption (PSA), and it may comprise further appliances for purification of hydrogen and for recycling of methane. Stream 7 hence designates a product gas (hydrogen) discharged from the purification unit 105, and stream 11 designates a recycle gas (such as methane and, in some instances, hydrogen), which can be (re)used for heating fluids/gases in the rotary heater 100 (as a stream 13). Recycle gas 11 can also be (re)used as a reactant in processes involving direct heating of methane as a process fluid. Therefore, it is important to adjust a composition of the recycle gas stream 11 (e.g. an amount of hydrogen and heavier hydrocarbons therein) in order to achieve favourable conversion and selectivity.

In addition to hydrogen, the process schematically depicted on Fig. 3 enables production of other valuable chemicals including, but not limited to ethane, ethylene, acetylene and benzene. Production of said compounds can be achieved by pyrolysis of methane obtained from natural gas or biogas for example, at high temperatures, preferably at temperatures exceeding 1500 °C, whereby very short residence time is needed to minimize carbon production. Any other suitable hydrocarbon-containing feedstock can be utilized, as indicated above. Thermal and/or catalytic pyrolysis is carried out in the reactor or reactors 101A, 101B, while heating to required temperatures may be performed in the rotary apparatus 100 (with optional booster heating in 103).

To avoid loss of selectivity towards valuable hydrocarbons and carbon formation, quench is needed to stop reactions immediately after reactor 101A. Only one reactor 101A can be used in order to minimize residence time therein and to optimize selectivity. In thermal pyrolysis, a quench unit can be arranged immediately after the reactor 101A in order to stop the reactions and thus avoid the loss of selectivity towards valuable hydrocarbons and carbon formation.

Quench unit is not shown on Fig. 3; however, such quench unit is a conventional part of heat recovery 104 and typically it consists of a high-pressure steam generator or involves direct injection of cooling media. In case the catalyst is used, the temperature in the reactor 101 (101A, 101B) can be lower and quench may not be needed. Provision of a quench unit is typically required in the process of producing hydrocarbons; however, in the production of hydrogen it can be omitted.

It is noted that both processes depicted on Fig. 3 (production of hydrogen and production of other hydrocarbons / chemicals) support recycling of gases, such as methane and a fraction of hydrogen. In production of hydrogen, the recycle gas is typically methane, while in the process adapted for production of hydrocarbons, the recycle gas is a mixture of hydrogen and methane.

Air or pure oxygen (8) can be optionally injected into the stream 3 exiting the rotary heater apparatus 100 in order to increase the temperature of methane gas before the pyrolysis reactor 101 (101A). In some instances, a part of a hydrogen product can be burned with oxygen in a separate chamber (not shown), and a hot steam thus formed can be mixed with the stream entering the reactor 101 (101A). Alternatively, only oxygen 8 can be injected to the hot methane gas directed to the reactor 101. The latter procedure will produce (water) steam and carbon oxides (CO and CO_2). However, this may put additional burden onto the purification section 105 to remove CO/CO_2 from the product gas 6. In described procedures involving air/oxygen injection between 100 and 101, the stream 3 exiting the rotary apparatus 100 may be propagated directly to hydrogen production 101; therefore, provision of the booster heater 103 may be optional.

Figs. 4A-4C schematically illustrate integration of the rotary apparatus 100 into a process of hydrogen production via the process of steam methane reforming (SMR). Same process can be used for the production of syngas.

In conventional steam methane reforming, methane is passed together with steam through a catalyst bed located in reforming tubes that are externally heated with a fired heater. Present disclosure teaches that the rotary apparatus can replace fuel-fired heaters in the catalytic and non-catalytic SMR processes.

Present disclosure describes at least two separate ways of integrating the rotary apparatus 100 into a process of steam methane reforming.

In an embodiment, the rotary apparatus acts as a (direct) heater that increases temperature of a methane–steam mixture or a natural gas–steam mixture propagating through the apparatus to a level required by the reforming reaction to take place. In case catalytic reforming reactions

occur at about 800–900 °C, the rotary apparatus 100 is required to heat the methane-steam mixture to the temperatures above about 1000 °C, since the endothermic reforming reaction reduces the temperature of the mixture in a catalyst bed, as the reaction progresses. Non-catalytic reforming reactions occur at about 1100°C, in which case the rotary apparatus 100 is required to heat the methane-steam mixture to temperatures above about 1300°C.

Figure 4A thus illustrates application of the rotary apparatus as a direct heater in steam methane reforming. Facility layout of Fig. 4A is applicable in any one of catalytic and non-catalytic SMR.

An arrangement shown for example on Figs. 2A, 2B can be utilized. Reference number 101 designates a heat-consuming unit/-utility configured, in this embodiment, as a reactor configured to perform steam reforming of methane to yield hydrogen and carbon oxide. In some instances, the reactor 101 is configured as a catalytic reforming reactor.

Direct heating involves propagating of an optionally preheated feed-containing process fluid, such as a mixture of methane with steam or natural gas with steam through the rotary apparatus 100, wherein said mixture is heated to a predetermined temperature. Preheater 102 is not shown. Preheated and desulfurized feed, such as natural gas (NG) undergoes heating in at least one apparatus 100 and it is further directed into the process unit 101 represented by the SMR reactor. In some configurations, the apparatus 100 can act as a pre-reformer, configured to pre-reform natural gas with steam (see “High-pressure steam” stream, Fig. 4A), whereby long-chain hydrocarbons are decomposed into methane and syngas. Syngas can be withdrawn from the process at this stage (not shown). Alternatively, the pre-reformer may be arranged within the unit 101.

The SMR reactor (unit 101) can be any conventional reactor adapted to implement reforming reactions. The reactor can be designed for the processes of catalytic or non-catalytic steam methane reforming. Exemplary SMR reactor may be a packed bed reactor. A mixture of methane and steam is heated in the apparatus 100 up to about 1000 °C (this temperature may vary depending on presence/absence of the catalyst) and is further directed into the SMR reactor 101, where reforming reactions occur (according to Equation 1a). The rotary apparatus 100 thus replaces fuel-fired heaters normally surrounding the reforming tubes (101). A high temperature water gas shift (WGS) unit/reactor can be arranged downstream of the main SMR reactor to increase hydrogen yield (Equation 1b). The product stream discharged from the SMR reactor 101 or from the water gas shift reactor proceeds to heat recovery 104 and to purification 105. Heat recovery may involve cooling and condensation of water and include a cooler/water condenser device. Purification may be implemented via pressure swing adsorption (PSA) or

any other suitable method. From the unit 105 purified hydrogen can be sent for utilization / storage (rf. "Hydrogen product" stream) and for recycle (rf. "Hydrogen recycle" stream). Not converted methane can also be sent to recycle from the unit 105 (rf. "Methane recycle" stream).

In some instances, in order to bring a reforming reaction into completion and/or to reach the desired extent of reaction, it may be beneficial to use additional "rotary apparatus 100 – SMR reactor 101" sequences (rf. dashed box on Fig. 4A). The SMR reactors in such sequences may be a catalyst bed reactor 101. Also for non-catalytic reforming, several sequences of 100 and 101 may be beneficial in order to optimize the residence times required for the reaction to proceed to completion. By way of example, but not limitation, one (1) to ten (10) such sequences may be successively arranged within a facility 1000.

Simulations, in which reactors 101 are assumed to run to equilibrium conditions considering the two main reactions SMR (Equation 1a) and WGS (Equation 1b), give an estimate of a number of required sequences. The simulations consider a pressure of 20 bar and a steam to methane ratio of 3:1. Feed to the system was 370°C at which temperature desulfurization is performed (rf. Fig. 4A).

For catalytic reforming involving an arrangement sequence of 100-101, heating the feed to 1000°C (reactor inlet temperature) in the rotary apparatus 100 leads to a methane conversion of about 37% in the outlet of the reactor 101, at which time the temperature will drop to about 650°C. Use of three (*i-iii*) consecutive sequences 100-101 (Fig. 5A) in which the inlet to each reactor 101 is heated to 1000°C results in a methane conversion of 78 %, which is more conventional at the tested pressure level.

Fig. 5A schematically illustrates alternating sequences (*i-iii)*, of rotary apparatuses 100 with catalytic gas phase reactors 101. Rotary apparatus 100 is used as a direct heater of gaseous feed and other reactants. Gaseous feed is thus heated to a maximum allowed temperature (often set by catalyst temperature tolerance and rate of undesired side reactions) and fed into a first catalytic reactor 101 according to Figure 5A. Reactants are thus heated before they enter the reactor 101. In 101, the reaction is allowed to take place with consequent adiabatic temperature decrease, thereafter the outflow is reheated in the next rotary apparatus 100 to be fed into the next reactor 101 in case desired conversion is not achieved.

For non-catalytic reforming involving an arrangement sequence of 100-101, a reactor inlet temperature of 1300°C can yield a maximum methane conversion of 59%, at which time the temperature will drop to about 745°C. Adding a second sequence can raise conversion rate up to 95%. Optimization of the process is possible by using consecutive rotary apparatus-reactor (100-101) sequences and by adjusting the temperatures and/or residence times allowed for the

reaction before the next heating stage. While the total power required for heating is determined by the reaction heat of the endothermic reaction and the reaction extent/conversion, the number of sequences and the temperature level can be adjusted to optimize the process yield and cost.

In some instances, a combination of two processes (heating in 100 and reaction in 101) may be realized in a single unit, where heating and reactions take place in the same piece of equipment. Such an arrangement is particularly beneficial in non-catalytic SMR (Fig. 4B).

Exemplary facility layout designed particularly for non-catalytic SMR is shown in more detail on Fig. 4B. In the non-catalytic SMR facility, the rotary heater 100 and the SMR reactor 101 may be combined in a single piece of equipment. In configuration comprising the at least one rotary apparatus 100 combining both heater (feed preconditioner) and reactor functionalities, provision of a preheater 102 may be omitted. Combined solution 100-101 utilizes lower pressures, which improves reaction yield. Moreover, the layout of Fig. 4B allows for transferring a sulphur removal step downstream of the reformer 101, as there is no catalyst to poison. Presence of sulphur in feed may further reduce coking.

In another embodiment, the rotary apparatus 100 is an indirect heater configured to heat any suitable gas (heat transfer medium), thereafter said hot gas heated in 100 is fed into the hydrogen production process/-unit 191, such as into a reforming furnace, for example. Hot gas produced in the rotary apparatus 100 enters the inner space of the furnace and heats reformer tubes to a necessary reaction temperature. In such a way, the apparatus 100 can replace fuel-fired external burners in the furnace. Such an arrangement is beneficial in a sense that the most of existing infrastructure could be utilized.

Figure 4C illustrates application of the rotary apparatus as an indirect heater in steam methane reforming. The rotary apparatus replaces a fired heater in the reformer furnace 101. The layout of Fig. 4C can utilize an arrangement shown for example on Figs. 2C, 2D and/or 2F.

The main difference of layouts shown on Figs. 4A, 4B (direct heating) and 4C (indirect heating) is that in the layouts of Figs. 4A and 4B the rotary apparatus(es) is/are used to (directly) heat the feed-containing process fluid (e.g. methane-steam mixture) wherefrom the heated fluid is directed into the steam reformer 101, whereas in the layout of Fig. 4C the rotary apparatus 100 is configured to heat a fluidic medium other than feed/process fluid (which could be referred to as a heat transfer medium, for clarity) From Fig. 4C one may observe that any suitable gas (e.g. make-up gas, air, nitrogen or steam) can be used as a heat transfer medium to be heated in the apparatus 100. Heat transfer media is further directed to the heat-consuming unit 101, such as a reformer furnace, to externally heat the reformer tubes. Methane containing feed and optionally steam needed for reforming reactions are supplied into the reformer 101 from

elsewhere (thus bypassing the rotary apparatus 100). Heat needed for endothermic reforming reactions to proceed in reformer 101 is thus supplied into the reformer 101 through a process of heat transfer between the heated fluidic medium (air, nitrogen, steam, etc.) generated in the rotary apparatus 100 and the process streams (methane, steam) bypassing the rotary apparatus 100.

Recycling of heat transfer medium can be implemented, in the indirect heating arrangement, as shown on Fig. 2D, for example. Heat transfer medium cooled in the unit 101 (hereby, in reformer furnace) as a result of heat transfer between said heat transfer medium and the process fluid (methane, steam), can be sent for reheating (as stream 9 shown on Fig. 2D). In such a way, heat losses can be minimized. Accordingly, also hydrogen product and unreacted methane can be recycled (recycling of methane is not shown on Fig. 4C).

Fig. 5B is a simplified layout that shows retrofitting the existing reformer furnace 101 with the rotary apparatus 100, where the apparatus 100 replaced fired heating. Figure 5B schematically illustrates an arrangement comprising at least one reactor or furnace 101 configured to perform a process or processes related to hydrogen production at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C) and at least one rotary apparatus 100 configured to generate a heated fluidic medium for inputting thermal energy into said at least one reactor or furnace.

In the layout of Fig. 5B, the at least one rotary apparatus 100 is used to replace fuel-fired radiant heater burners external to the furnace/reactor 101. The rotary apparatus 100 is used as an indirect heater to heat an inert gas, such steam, air or nitrogen, which is further fed into a refractory space of the furnace 101, similarly to fuel in fired heaters. Hot gas from the rotary apparatus would provide heating to catalytic reactor tubes inside the furnace. The inert gas heated by the apparatus 100 acts hereby as a heating medium/heat transfer medium for the process fluid propagated through the tubes/coils inside the furnace 101. The process fluid can be gas (e.g. methane gas), liquid or gas-liquid mixture.

In configuration of Fig. 5B, flue gases (e.g. N_2, CO_2, H_2O, NO_x, SO_x, particulate matter) exiting from the furnace may be further used as an input flow to the rotary apparatus for reheating (see a Flue gas recycle line, Fig. 5B).

Additional advantage of the rotary apparatus 100 here is that it acts as a blower, providing necessary pressure increase for the fluid to circulate. Hence, the layout eliminates the need for a separate air blower (typical to conventional fired furnaces).

Using the rotary apparatus as a recirculating heater allows for optimal heat recovery from the flue gas and ensures that heat losses are minimised. In this embodiment, also harmful environmental emissions like carbon dioxide, nitrogen oxides, sulphur oxides and particulate emissions are avoided.

Circulating the inert gas, such as for example steam or nitrogen, in the rotary apparatus 100 is advantageous particularly in case the fluid to be heated is at high pressure and/or it is flammable. This would provide inert atmosphere in the furnace to improve process safety.

Overall, Figs. 5A and 5B provide an overview of integrating the rotary apparatus 100 with the catalytic reactors adapted for endothermic reactions. Fired heaters and furnaces that provide heat for high-temperature endothermic catalytic reactions account for a grand majority of all emissions in hydrogen production industry, such as for example through (catalytic) methane steam reforming. The rotary apparatus 100 can be used to provide thermal energy for such catalytic reactions by heating the feed of the catalytic reactors 101 and introducing hot feed to catalytic beds with ascending temperature profile. To maintain reaction rate and to bring the reactions into completion, the rotary apparatus can act as a reheater between said catalytic beds (rf. Figs. 2E, 5A).

Figs. 5A and 5B illustrate integrating the rotary apparatus 100 into the most common routes of supplying the heat of reaction into endothermic, solid-catalysed reaction processes as follows: 1) to expose catalyst-containing tubes to external heating, for continuously introducing heat through reactor tube to catalyst bed and reactants along the length of the catalyst bed (Fig. 5B, indirect heating); and 2) to heat the reactants to a high temperature before they enter the reactor, allow reaction to take place with consequent adiabatic temperature decrease and then reheat the reactants for next reactor in case desired conversion is not achieved (Fig. 5A, direct heating). The concept of Fig. 5B is suitable for retrofitting existing furnaces. For new, "greenfield" installations direct heating of gas in the rotary apparatus could be applied (Fig. 5A). The layout of Fig. 5A can be integrated into a catalytic gasoline reforming process (typically performed in a semi-regenerative catalytic reformer unit in a petroleum refinery). The rotary apparatus 100 can be directly applied by replacing the fired heaters, as described hereinabove.

It is clear to a person skilled in the art that with the advancement of technology the basic ideas of the present invention may be implemented and combined in various ways. The invention and its embodiments are thus not limited to the examples described herein above, instead they may generally vary within the scope of the appended claims.

Claims

1. A method for inputting thermal energy into a process or processes related to producing hydrogen in a hydrogen production facility, the method comprises generation of a heated fluidic medium by at least one rotary apparatus integrated into the hydrogen production facility, the at least one rotary apparatus comprising:

a casing with at least one inlet and at least one exit,

a rotor comprising at least one row of rotor blades arranged over a circumference of a rotor hub mounted onto a rotor shaft, and

a plurality of stationary vanes arranged into an assembly at least upstream of the at least one row of rotor blades,

the method further comprises:

- integrating the at least one rotary apparatus into the hydrogen production facility configured to carry out process or processes related to hydrogen production at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C),
- conducting an amount of input energy into the at least one rotary apparatus integrated into the hydrogen production facility, the input energy comprising electrical energy, and
- operating the at least one rotary apparatus integrated into the hydrogen production facility such, that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary vanes and the at least one row of rotor blades, respectively, whereby a stream of heated fluidic medium is generated.

2. The method of claim 1, comprising connecting, in said hydrogen production facility, the at least one rotary apparatus to at least one reactor or furnace configured to produce hydrogen from hydrocarbon-containing gas.

3. The method of any one of claims 1 or 2, wherein the at least one reactor or furnace is configured to carry out thermal and/or catalytic processes to generate hydrogen from the hydrocarbon-containing gas.

4. The method of any preceding claim, wherein the hydrogen production facility is a methane pyrolysis plant or a steam methane reforming (SMR) plant.

5. The method of any preceding claim, comprising generation, by at least one rotary apparatus, of the fluidic medium heated to the temperature essentially equal to or

exceeding about 500 degrees Celsius (°C), preferably, to the temperature essentially equal to or exceeding about 1200 °C, still preferably, to the temperature essentially equal to or exceeding about 1700 °C.

6. The method of any preceding claim, comprising adjusting velocity and/or pressure of the stream of fluidic medium propagating through the rotary apparatus to produce conditions, at which the stream of the heated fluidic medium is generated.

7. The method of any preceding claim, in which the heated fluidic medium is generated by at least one rotary apparatus comprising two or more rows of rotor blades sequentially arranged along the rotor shaft.

8. The method of any preceding claim, in which the heated fluidic medium is generated by at least one rotary apparatus further comprising a diffuser area arranged downstream of the at least one row of rotor blades, the method comprises operating the at least one rotary apparatus integrated into the hydrogen production facility such, that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium successively passes through the stationary vanes, the rotor blades and the diffuser area, respectively, whereby a stream of heated fluidic medium is generated.

9. The method of any preceding claim, wherein, in said rotary apparatus, the diffuser area is configured with or without stationary diffuser vanes.

10. The method of any preceding claim, in which the amount of thermal energy added to the stream of fluidic medium propagating through the rotary apparatus is controlled by adjusting the amount of input energy conducted into the at least one rotary apparatus integrated into the hydrogen production facility.

11. The method of any preceding claim, further comprising arranging an additional heating apparatus downstream of the at least one rotary apparatus and introducing a reactive compound or a mixture of reactive compounds to the stream of fluidic medium propagating through said additional heating apparatus, whereupon the amount of thermal energy is added to said stream of fluidic medium through exothermic reaction(s).

12. The method of claim 11, wherein the reactive compound or a mixture of reactive compounds is introduced to the stream of fluidic medium preheated to a predetermined temperature.

13. The method of claim 12, wherein the reactive compound or a mixture of reactive compounds is introduced to the stream of fluidic medium preheated to a temperature essentially equal to or exceeding about 1700 °C.

14. The method of any preceding claim 11-13, wherein preheating of the stream of fluidic medium to the predetermined temperature is implemented in the rotary apparatus.

15. The method of any preceding claim, comprising generation of the heated fluidic medium by at least two rotary apparatuses integrated into the hydrogen production facility, wherein the at least two rotary apparatuses are connected in parallel or in series.

16. The method of claim 15, comprising generation of the heated fluidic medium by at least two sequentially connected rotary apparatuses, wherein the stream of fluidic medium is preheated to a predetermined temperature in at least a first rotary apparatus in a sequence, and wherein said stream of fluidic medium is further heated in at least a second rotary apparatus in the sequence by inputting an additional amount of thermal energy into the stream of preheated fluidic medium propagating through said second rotary apparatus.

17. The method of claim 16, wherein, in at least the first rotary apparatus in the sequence, the stream of fluidic medium is preheated to a temperature essentially equal to or exceeding about 1700 °C.

18. The method of any one of claims 16 or 17, wherein the additional amount of thermal energy is added to the stream of fluidic medium propagating through said at least second rotary apparatus in the sequence by virtue of introducing the reactive compound or a mixture of compounds into said stream.

19. The method of any preceding claim, comprising introducing the reactive compound or a mixture of compounds into the process or processes related to hydrogen production.

20. The method of any preceding claim, in which the heated fluidic medium generated by the at least one rotary apparatus is selected from the group consisting of a feed gas, a recycle gas, a make-up gas, and a process fluid.

21. The method of any preceding claim, wherein the fluidic medium that enters the rotary apparatus is an essentially gaseous medium.

22. The method of any preceding claim, comprising generation of the heated fluidic medium in the rotary apparatus.

23. The method of claim 22, wherein the heated fluidic medium generated in the rotary apparatus is a hydrocarbon-containing gas.

24. The method of claim 23, wherein the hydrocarbon-containing gas heated in the rotary apparatus comprises or consists of methane, natural gas or a mixture thereof.

25. The method of claim 22, wherein the heated fluidic medium generated in the rotary apparatus comprises or consists of a gaseous medium other than the hydrocarbon-containing gas, such air, steam (H_2O), nitrogen (N_2), or any combination thereof.

26. The method of claim 22, wherein the heated fluidic medium generated in the rotary apparatus comprises or consists of a recycle gas recycled from exhaust gases generated during hydrogen production process(es) in the hydrogen production incineration facility.

27. The method of any preceding claim, further comprising generation of the heated fluidic medium outside the rotary apparatus through a process of heat transfer between the heated fluidic medium generated in the rotary apparatus and a stream of fluidic medium bypassing the rotary apparatus.

28. The method of claim 27, comprising generation of the heated fluidic medium, provided as a hydrocarbon-containing gas, outside the rotary apparatus through a process of heat transfer between the heated fluidic medium other than said hydrocarbon-containing gas generated in the rotary apparatus and a stream of fluidic medium provided as the hydrocarbon-containing gas and bypassing the rotary apparatus.

29. The method of any preceding claim, further comprising increasing pressure in the stream of fluidic medium propagating through the rotary apparatus.

30. The method of any preceding claim, in which the amount of electrical energy conducted as the input energy into the at least one rotary apparatus integrated in the hydrogen production facility is within a range of about 5 percent to 100 percent.

31. The method of any preceding claim, wherein the amount of electrical energy conducted as the input energy into the at least one rotary apparatus integrated in the hydrogen

production facility is obtainable from a source of renewable energy or a combination of different sources of energy, optionally, renewable energy.

32. The method of any preceding claim, wherein the at least one rotary apparatus is utilized to balance variations, such as oversupply and shortage, in the amount of electrical energy, optionally renewable electrical energy, by virtue of being integrated into the hydrogen production facility together with at least one non-electrical energy operable heater device.

33. A hydrogen production facility comprising at least one reactor or furnace configured to produce hydrogen from hydrocarbon-containing gas at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C) and at least one rotary apparatus configured to generate a heated fluidic medium for inputting thermal energy into said at least one reactor or furnace, the at least one rotary apparatus comprising:
a casing with at least one inlet and at least one exit,
a rotor comprising at least one row of rotor blades arranged over a circumference of a rotor hub mounted onto a rotor shaft, and
a plurality of stationary vanes arranged into an assembly at least upstream of the at least one row of rotor blades,
wherein said at least one rotary apparatus is configured to receive an amount of input energy, the input energy comprising electrical energy, and
wherein the at least one rotary apparatus is further configured to operate such that an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary guide vanes and the at least one row of the rotor blades, respectively, whereby a stream of heated fluidic medium is generated.

34. The hydrogen production facility of claim 33, wherein the at least one rotary apparatus comprises two or more rows of rotor blades sequentially arranged along the rotor shaft.

35. The hydrogen production facility of claim 33, wherein the at least one rotary apparatus further comprises a diffuser area arranged downstream of the at least one row of rotor blades.

36. The hydrogen production facility of claim 33, wherein the rotary apparatus comprises the diffuser area configured with or without stationary diffuser vanes.

37. The hydrogen production facility of claim 33, wherein the at least one rotary apparatus is further configured to increase pressure in the fluidic stream propagating therethrough.

38. The hydrogen production facility of any preceding claim 33-37, wherein at least two rotary apparatuses are arranged into an assembly and connected in parallel or in series.

39. The hydrogen production facility of any preceding claim 33-38 configured as a methane pyrolysis plant or a steam methane reforming (SMR) plant.

40. A hydrogen production facility configured to implement a process or processes related to production of hydrogen through a method as defined in any one of claims 1-32.

41. Use of the hydrogen production facility in accordance with any one of claims 33-38 for implementation of processes related to production of hydrogen and/or synthesis gas, optionally, through a process of steam-methane reforming.

42. Use of the hydrogen production facility in accordance with any one of claims 33-38 for implementation of processes related to conversion of methane to hydrogen, fuels and/or chemicals.

43. Use of the method in accordance with any one of claims 1-32 in a heat-consuming facility configured for- and/or in processes related to production of hydrogen and/or synthesis gas, optionally, through a process of steam-methane reforming.

44. Use of the method in accordance with any one of claims 1-32 in a heat-consuming facility configured for- and/or in processes related to conversion of methane to hydrogen, fuels and/or chemicals.

45. Use of the method in accordance with any one of claims 1-32 for improving energy efficiency of a hydrogen production facility and/or for reducing greenhouse gas and particle emissions in said hydrogen production facility.

46. A method for production of hydrogen, comprising inputting thermal energy into a process or processes related to producing hydrogen in a hydrogen production facility in accordance with a method defined in any one of claims 1-32.

47. A method for production of hydrogen, the method comprising generation of a heated fluidic medium by at least one rotary apparatus integrated into a hydrogen production facility, the at least one rotary apparatus comprising:
a casing with at least one inlet and at least one exit,

a rotor comprising at least one row of rotor blades arranged over a circumference of a rotor hub mounted onto a rotor shaft, and

a plurality of stationary vanes arranged into an assembly at least upstream of the at least one row of rotor blades,

wherein

an amount of thermal energy is imparted to a stream of fluidic medium directed along a flow path formed inside the casing between the inlet and the exit by virtue of a series of energy transformations occurring when said stream of fluidic medium passes through the stationary vanes and the at least one row of rotor blades, respectively, whereby a stream of heated fluidic medium is generated, the method further comprising:

- conducting an amount of input energy into the at least one rotary apparatus integrated into the hydrogen production facility, the input energy comprising electrical energy,
- supplying the stream of heated fluidic medium generated by the at least one rotary apparatus into the hydrogen production facility, and
- operating said at least one rotary apparatus and said hydrogen production facility to carry out hydrogen production at temperatures essentially equal to or exceeding about 500 degrees Celsius (°C).

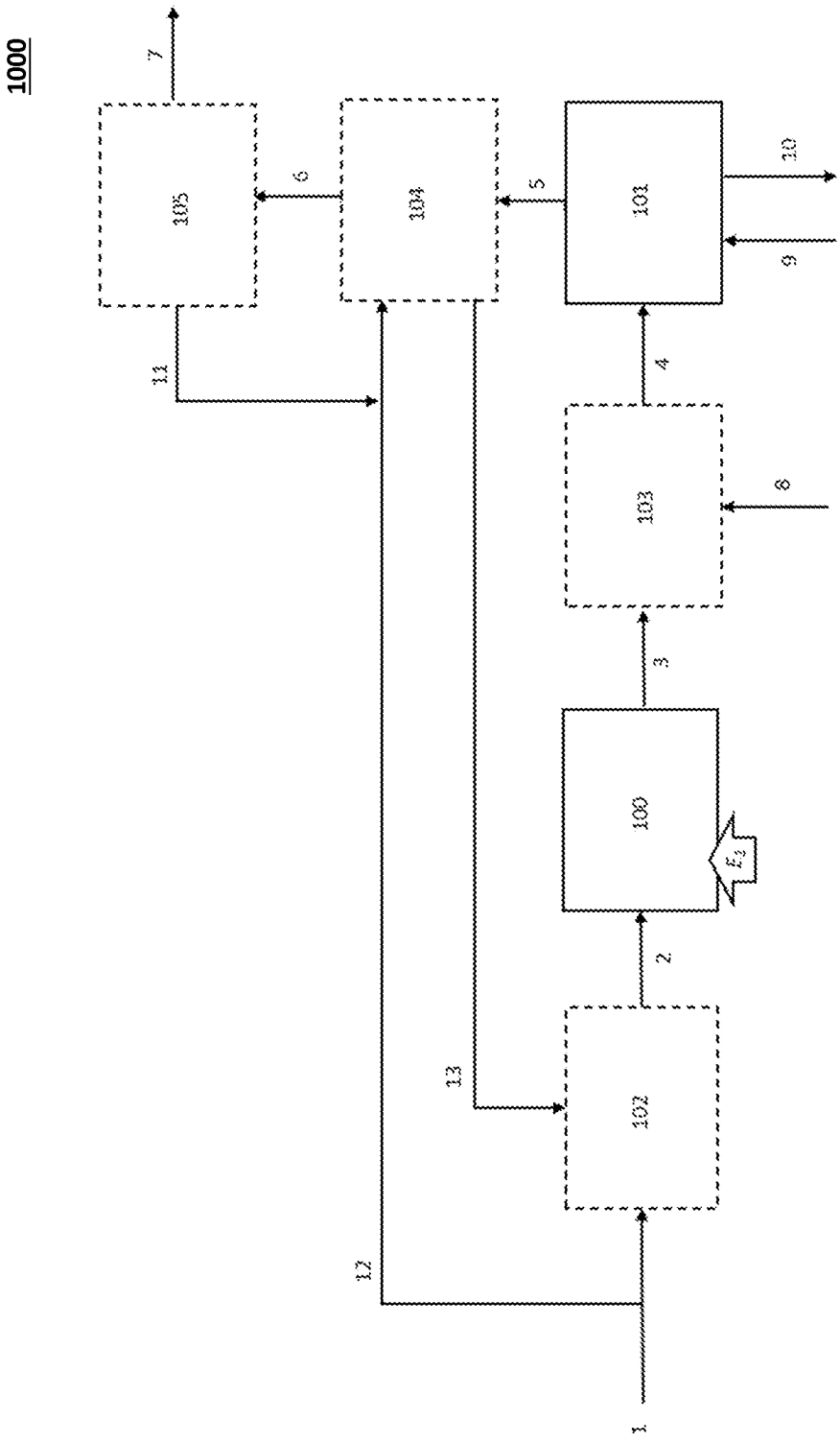


Figure 1

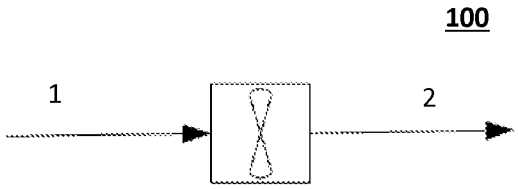


Figure 2A

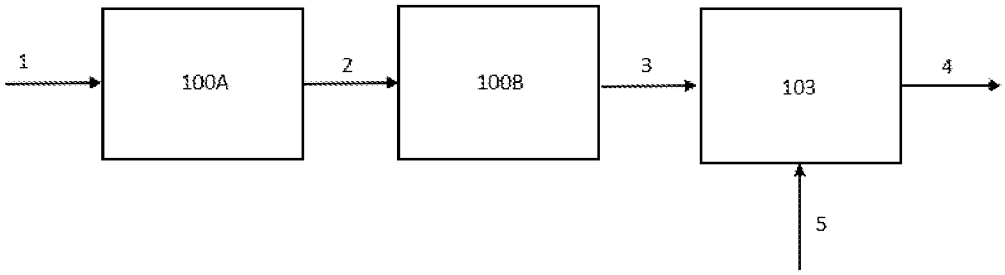


Figure 2B

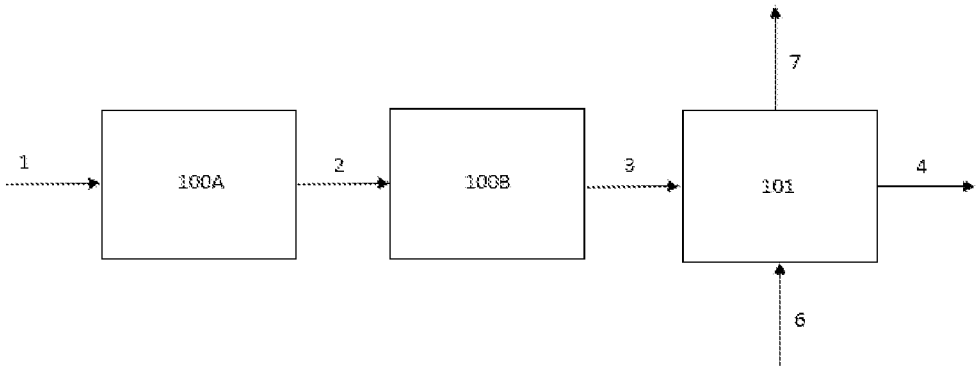


Figure 2C

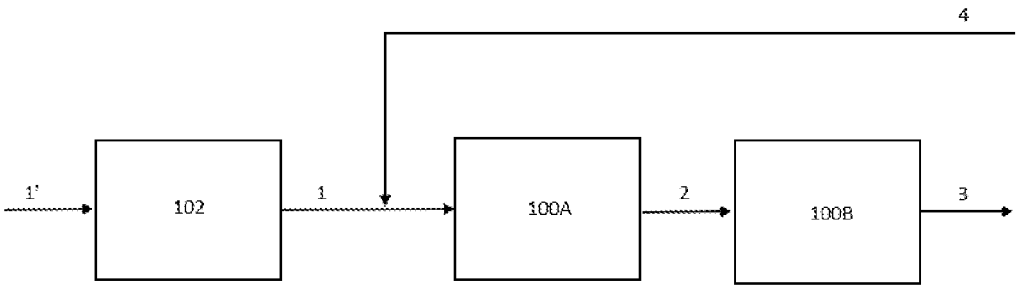


Figure 2D

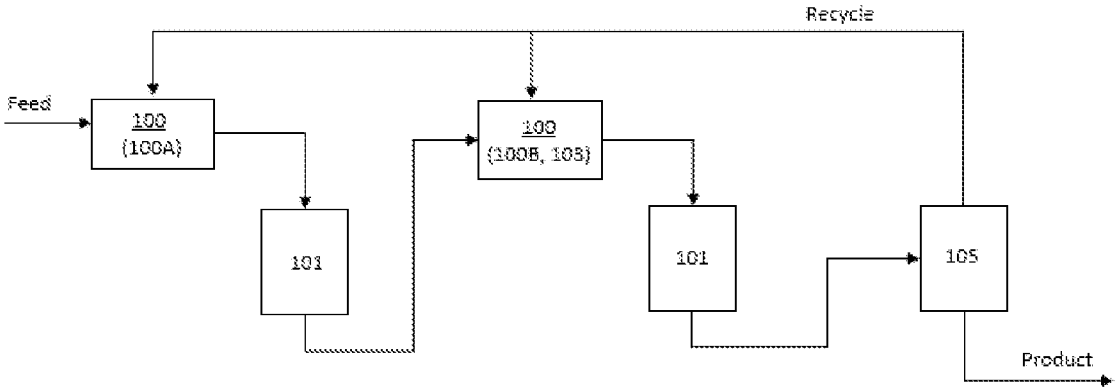


Figure 2E

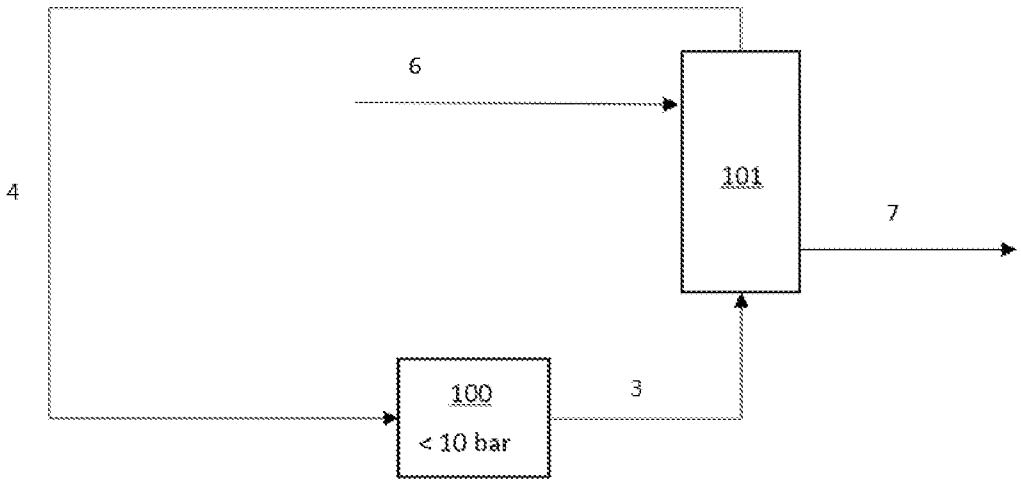


Figure 2F

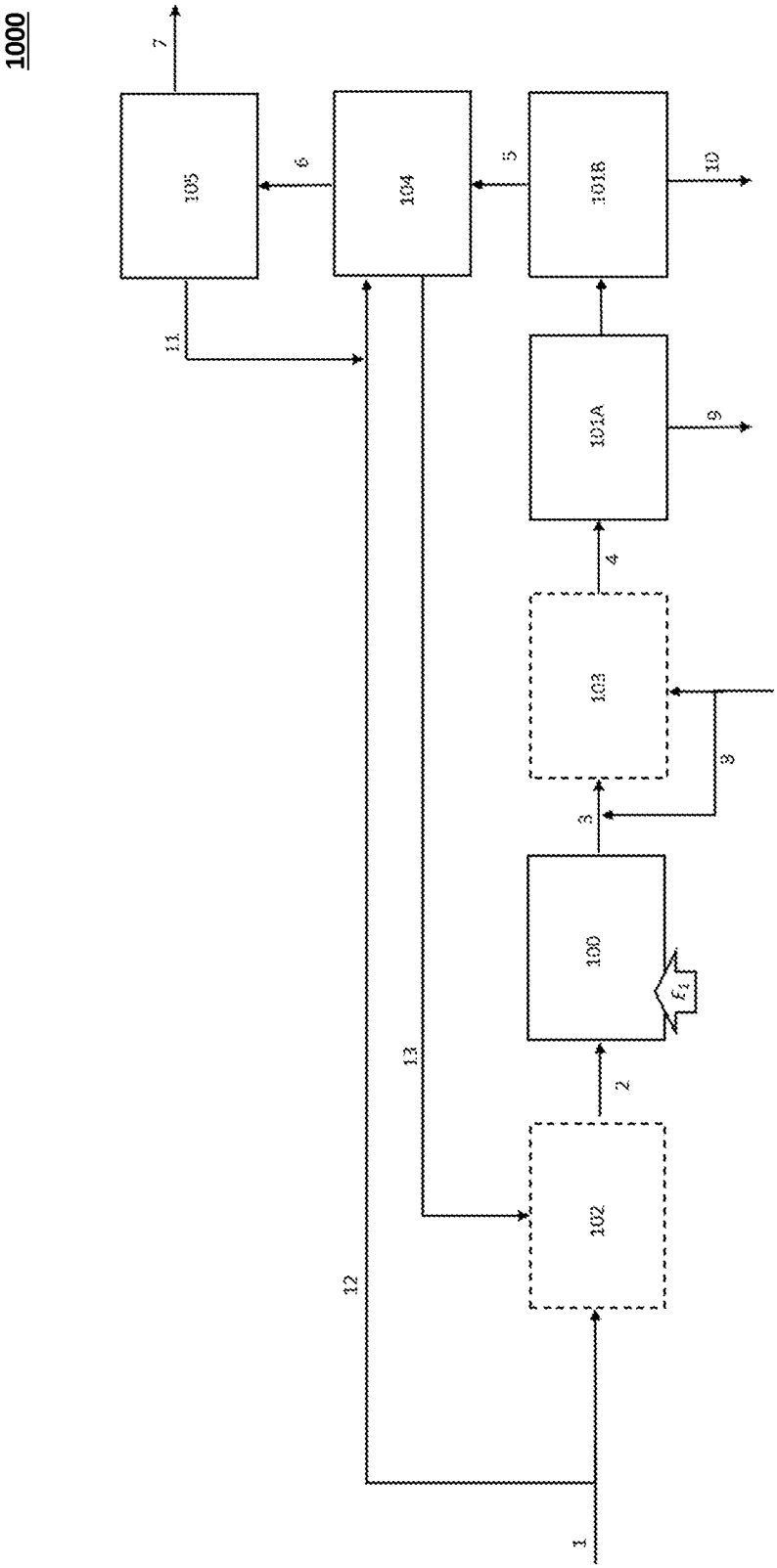


Figure 3

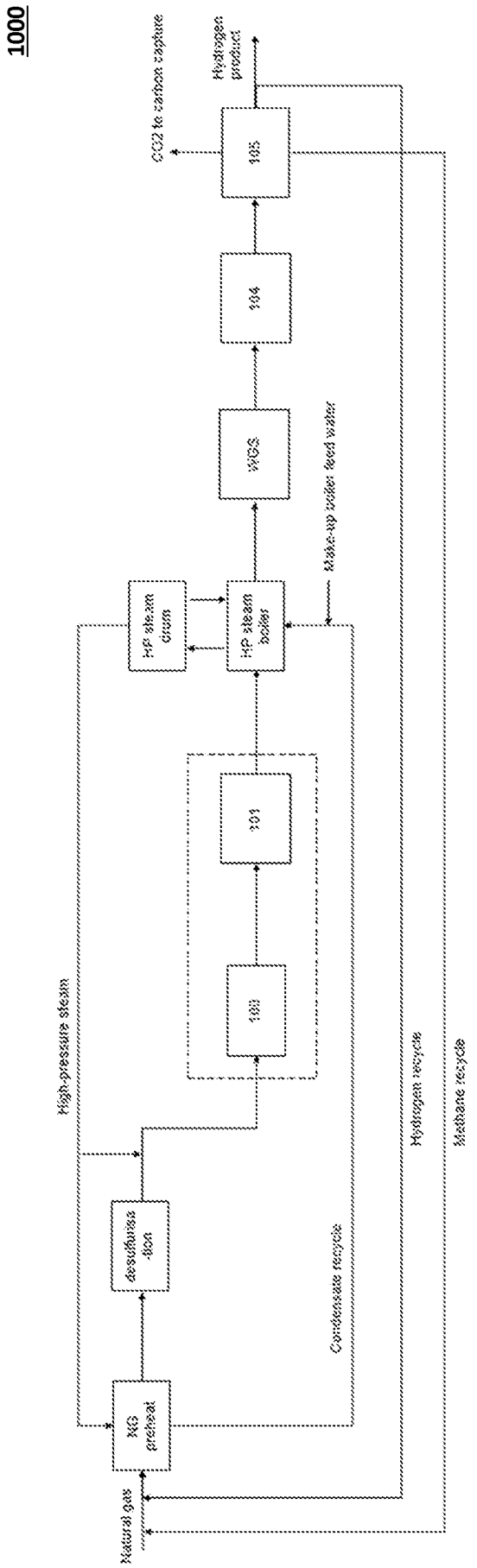

1000
CO2 to carbon capture
Hydrogen product
105
104
WGS
Make-up boiler feed water
HP steam drum
HP steam boiler
101
103
High-pressure steam
Condensate recycle
Hydrogen recycle
Methane recycle
desulphuriser
NG preheat
Natural gas

Figure 4A

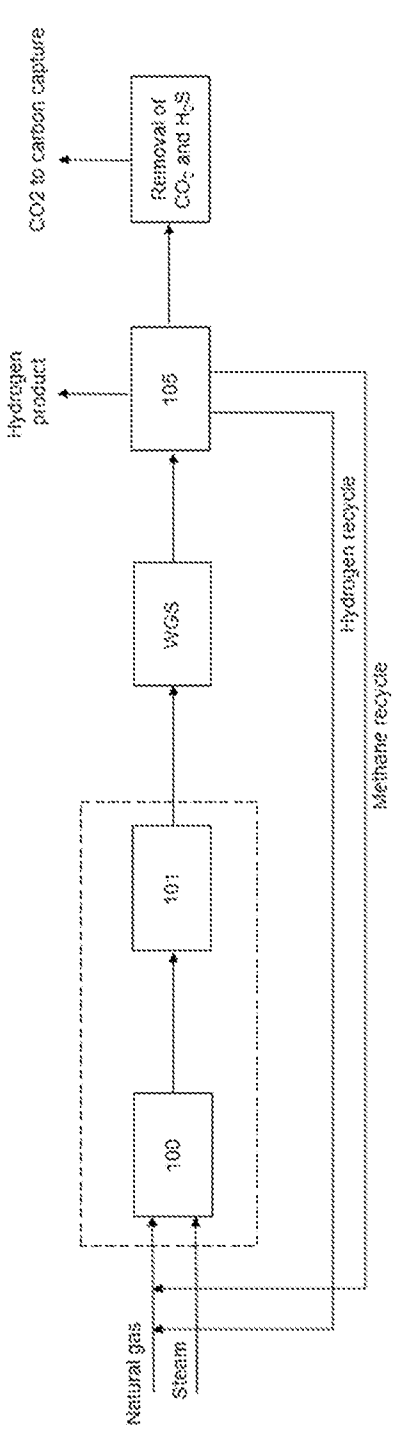

1000
CO2 to carbon capture
Removal of CO2 and H2S
hydrogen product
105
WGS
101
100
hydrogen recycle
Methane recycle
Natural gas
Steam

Figure 4B

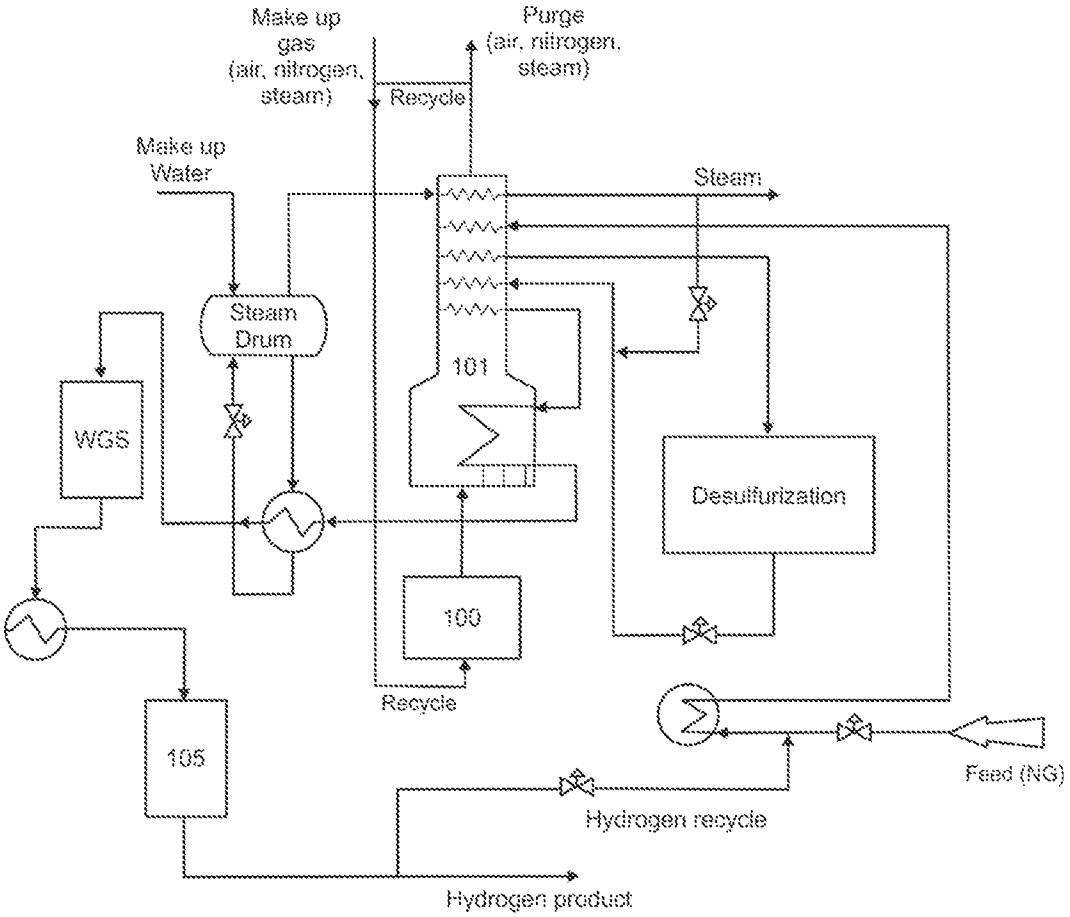

Make up gas (air, nitrogen, steam)
Purge (air, nitrogen, steam)
Recycle
Make up Water
Steam
Steam Drum
101
WGS
Desulfurization
100
Recycle
105
Feed (NG)
Hydrogen recycle
Hydrogen product

Figure 4C

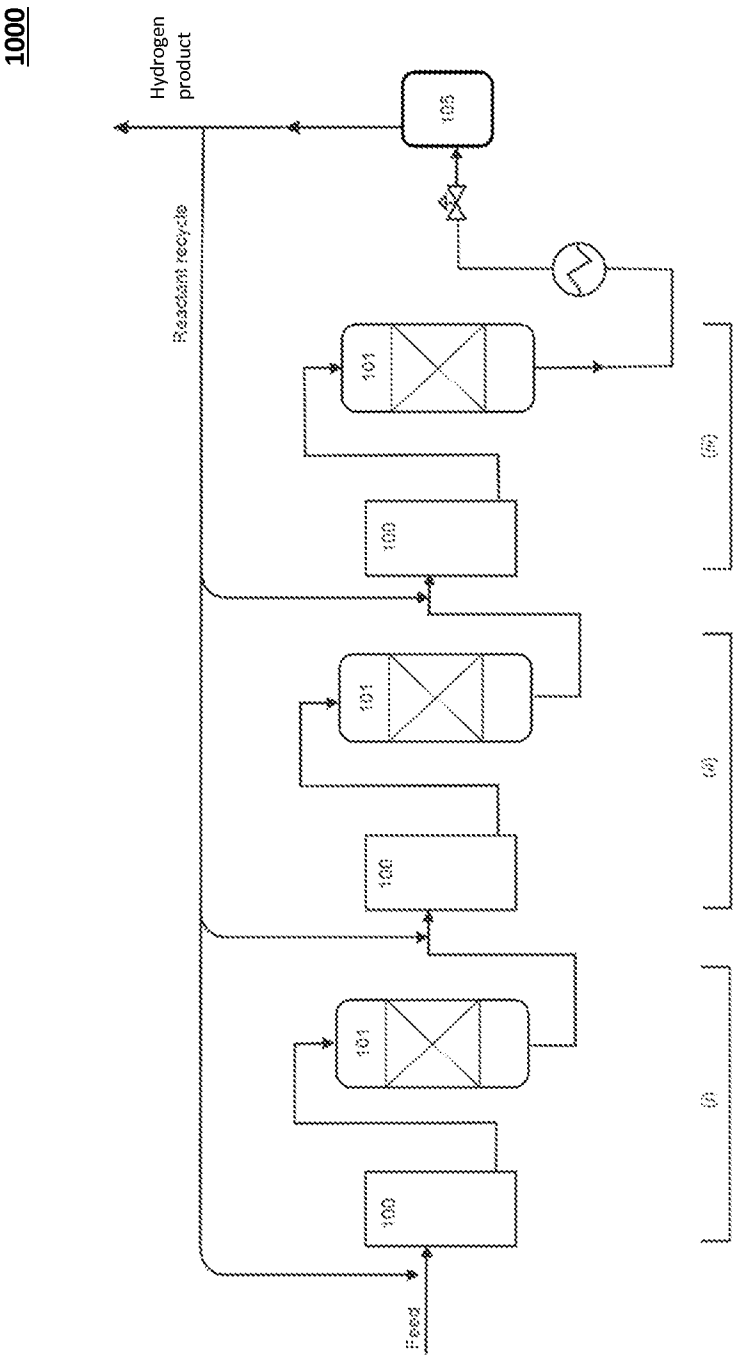

1000
Hydrogen product
Reactant recycle
Feed
105
101
103
101
103
101
103
(3)
(2)
(1)

Figure 5A

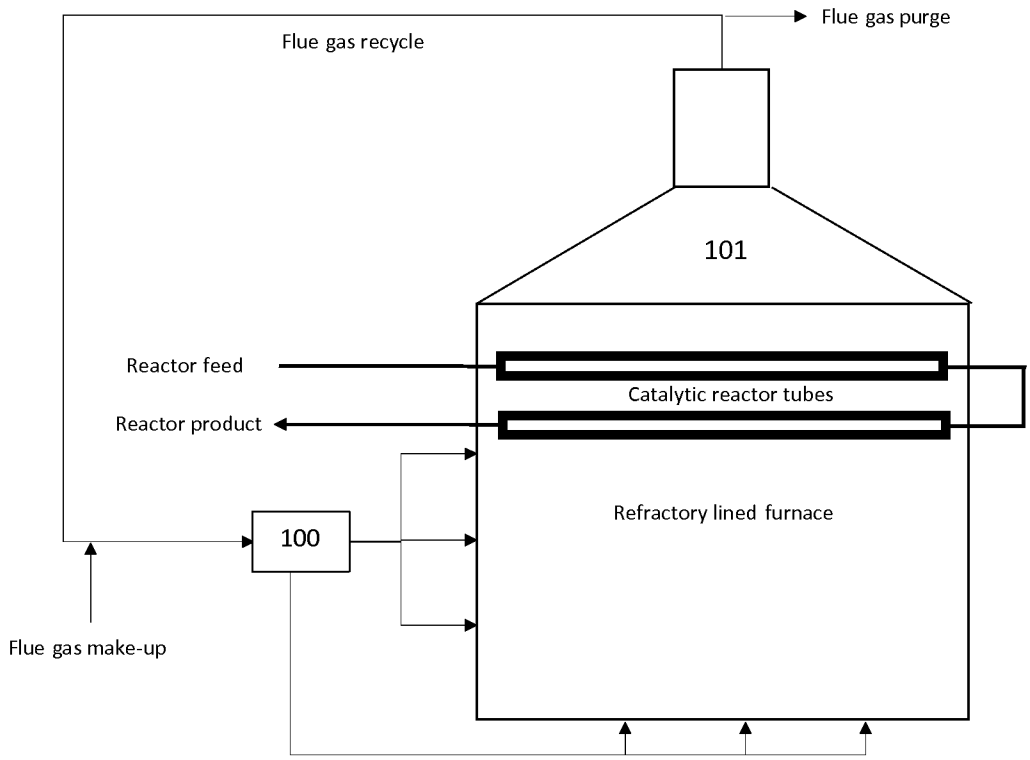

Flue gas purge
Flue gas recycle
101
Reactor feed
Catalytic reactor tubes
Reactor product
Refractory lined furnace
100
Flue gas make-up

Figure 5B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI2022/050684

A. **CLASSIFICATION OF SUBJECT MATTER**

See extra sheet

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)

IPC: B01J, F24V, C01B, B01F, F04D, C10G, F01D, F02C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

FI, SE, NO, DK

Electronic data base consulted during the international search (name of data base, and, where practicable, search terms used)

EPODOC, EPO-Internal full-text databases, Full-text translation databases from Asian languages, WPIAP, IPRally, PRH-Internal, XPESP, COMPDX, Inspec, Google.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1063273 A1 (COOLBROOK LTD [VG]) 27 December 2000 (27.12.2000) the whole document, especially abstract; paragraphs [0016], [0017], [0020], [0021], [0029], [0033], [0046]–[0050], [0054], [0058]; Figs 1–3; claims 1–4	1-47
A	US 2014243569 A1 (SEPPALA JUKKA [FI] et al.) 28 August 2014 (28.08.2014) the whole document, especially abstract; paragraphs [0006]–[0013], [0018], [0025], [0035], [0038], [0073]–[0085], [0115]; Figs 1, 2; claims 1, 3, 4, 5, 6, 19–21, 31–36	1-47
A	US 2013280035 A1 (HUMMER KIRK D [US]) 24 October 2013 (24.10.2013) the whole document, especially abstract; paragraphs [0002]–[0004], [0037]–[0046], [0058], [0071]–[0075]; Figs 1–4; claims 1–6	1-47

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

* Special categories of cited documents:

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"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

"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

"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

"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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 December 2022 (21.12.2022)	23 December 2022 (23.12.2022)

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2020114332 A1 (XU LIPING [GB] et al.) 16 April 2020 (16.04.2020) the whole document, especially abstract; paragraphs [0002], [0012]–[0025], [0070]–[0083]; Figs 1, 2; claims 1–9, 18, 19, 39–42	1-47
A	US 2005210881 A1 (BALAN CHELLAPPA [US] et al.) 29 September 2005 (29.09.2005) the whole document, especially abstract; paragraphs [0001], [0006]–[0008], [0018]–[0023], [0043]; Fig. 1; claims 1–21	1-47

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI2022/050684

CLASSIFICATION OF SUBJECT MATTER

IPC
B01J 19/18 (2006.01)
F24V 40/00 (2018.01)
B01J 3/00 (2006.01)
C01B 3/02 (2006.01)
B01J 6/00 (2006.01)

EP 1063273 A1	27/12/2000	AU 3280399 A	15/09/1999
		AU 753883 B2	31/10/2002
		BG 104710 A	31/07/2001
		BG 65376 B1	30/04/2008
		BR 9908329 A	14/11/2000
		CA 2323141 A1	02/09/1999
		CA 2323141 C	14/11/2006
		CN 1298439 A	06/06/2001
		DE 19982976 T1	08/03/2001
		DE 19982976 C2	19/12/2002
		GB 0021085 D0	11/10/2000
		GB 2353802 A	07/03/2001
		GB 2353802 B	07/08/2002
		GB 0207847 D0	15/05/2002
		GB 2372751 A	04/09/2002
		GB 2372751 B	09/10/2002
		HU 0100875 A2	28/06/2001
		HU 225699 B1	28/06/2007
		ID 27565 A	12/04/2001
		IL 138101 A	31/08/2005
		JP 2002504620 A	12/02/2002
		JP 3824488 B2	20/09/2006
		KR 20010024951 A	26/03/2001
		KR 100418360 B1	11/02/2004
		NO 20004287 D0	25/08/2000
		NO 20004287 L	27/10/2000
		PL 342965 A1	16/07/2001
		PL 191275 B1	28/04/2006
		RO 120574 B1	28/04/2006
		RU 2124039 C1	27/12/1998
		SK 285935 B6	02/11/2007
		TR 200002513 T2	21/06/2001
		UA 45503 C2	15/04/2002
		US 2005137440 A1	23/06/2005
		US 7232937 B2	19/06/2007
		WO 9943765 A1	02/09/1999
US 2014243569 A1	28/08/2014	US 9234140 B2	12/01/2016
US 2013280035 A1	24/10/2013	US 9528530 B2	27/12/2016
US 2020114332 A1	16/04/2020	US 10744480 B2	18/08/2020
		AU 2019356182 A1	03/06/2021

		AU 2019356182 B2	20/01/2022
		BR 112021006797 A2	20/07/2021
		BR 112021006797 B1	10/05/2022
		CA 3115879 A1	16/04/2020
		CA 3115879 C	26/04/2022
		CN 113015575 A	22/06/2021
		EA 202190990 A1	07/09/2021
		EP 3863761 A1	18/08/2021
		JP 2021534969 A	16/12/2021
		JP 7038258 B2	17/03/2022
		KR 20210092205 A	23/07/2021
		KR 102346861 B1	06/01/2022
		SG 11202103630W A	28/05/2021
		WO 2020074780 A1	16/04/2020
US 2005210881 A1	29/09/2005	US 7752848 B2	13/07/2010
		CN 1676460 A	05/10/2005
		CN 1676460 B	08/06/2011
		EP 1582502 A1	05/10/2005
		EP 1582502 B1	16/05/2018
		JP 2005281131 A	13/10/2005