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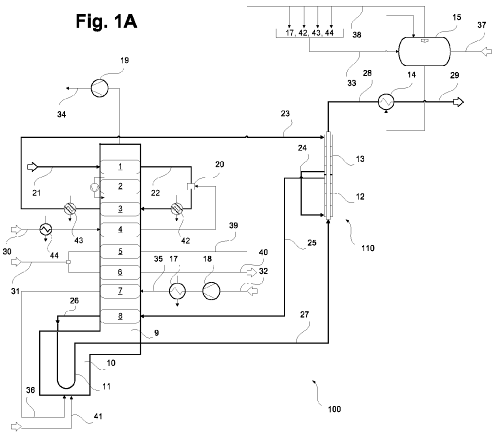
The references to figure 11 is deemed to be deleted (Rule 43 EPC 1973).

(54) METHODS AND APPARATUSES FOR PRODUCING OLEFINS

(57) A method to produce olefins comprising preheating a reaction feed, firing a conversion reactor, subjecting the reaction feed to a conversion in the conversion reactor, withdrawing a product gas from the conversion reactor, and cooling the product gas withdrawn from the conversion reactor is proposed, wherein said preheating and said cooling comprises transferring heat from said product gas or a part thereof to said reaction feed or a part thereof using a thermal energy recovery assembly comprising one or more inner passages and one or more outer passages coaxially surrounding said inner passage(s), said preheating and said cooling further comprises passing said reaction feed or said part thereof through said outer passage(s) of said thermal energy recovery assembly and passing said product gas or said part thereof through said inner passage(s) of said thermal energy recovery assembly, said thermal energy recovery assembly comprises one or more heat transfer enhancement structures to enhance heat transfer from said inner passage(s) to said outer passage(s), said firing the reactor comprises providing an oxidator gas at an oxidator gas temperature level of more than 400 °C using an oxidator gas preheating system and combusting a fuel gas comprising hydrogen using said oxidator gas at the fuel gas temperature level, and said thermal energy recovery assembly is configured to meet a set of operating constraints including a first temperature constraint relating to an outside temperature of a containment of said inner

passage of said thermal energy recovery assembly and a second temperature constraint relating to an inside temperature of the containment of said inner passage of said thermal energy recovery assembly. Corresponding apparatus is also disclosed.

Fig. 1A



Description

[0001] The present disclosure relates to methods and apparatuses for producing olefins.

BACKGROUND

[0002] Steam cracking of hydrocarbon feeds in gas-fired steam cracking furnaces is the predominant commercial method for producing olefins. In such methods, hydrocarbons like ethane, propane, butane, condensate, light naphtha, heavy naphtha, gas oil, pyrolysis oil, materials derived from processing refinery streams, Fischer-Tropsch products, plastic waste, or biofeedstocks are pre-heated state to typically 550 to 650 °C and are then further heated in a steam cracking furnace together with steam to temperatures sometimes approaching 850 °C to facilitate conversion to light olefins such as ethylene and propylene. As the cracking reactions involved in steam cracking are endothermic, significant amounts of heat must be provided.

[0003] To provide the energy required for conventional steam cracking processes, natural gas and/or light gas may be combusted in gas-fired steam cracking furnaces, usually with ambient air as an oxidator gas. Combustion of the hydrocarbons in the gas-fired steam cracking furnace forms carbon dioxide which is conventionally emitted as part of a flue gas from the gas-fired steam cracking furnace. Such emissions are generally undesirable in view of current environmental considerations.

[0004] Olefins, however are a major chemical building block and may often be produced in large quantities, from several hundred thousand tons per year in a small steam cracker to two million tons per year or more at a single large olefin production facility. As a result, the production of olefins using conventional gas-fired steam cracking furnaces may result in an undesirably high emission of carbon dioxide.

[0005] There is a need for improved methods and apparatuses for conversion reactions using fired reactors, particularly for endothermic reactions such as steam cracking.

SUMMARY

[0006] In view of the above, methods and apparatuses for producing olefins comprising the features of the independent claims are provided herein. Embodiments are the subject of the dependent claims and of the description that follows.

[0007] A method to produce olefins provided herein comprises preheating a reaction feed, firing a conversion reactor, subjecting the reaction feed to a conversion in the conversion reactor, withdrawing a product gas from the conversion reactor, and cooling the product gas withdrawn from the conversion reactor.

[0008] The reaction feed may comprise one or more hydrocarbons and may further comprise steam. At some places hereinbelow, reference is therefore made to a "hydrocarbon feed". The product gas may be a "crude gas" or "cracked gas" as generally known from the field of steam cracking or other conversion reactions, i.e. it may be a gaseous mixture of components generally unchanged, in its composition, from a composition it has directly at the outlet of the conversion reactor. The product gas may, or may have not, have undergone treatment steps such as compression when being treated as proposed herein. Herein, steam cracking mainly explained as an example conversion reaction and the conversion reactor may, in this example, a steam cracking furnace as generally known in the art. If, therefore, any referral is made to steam cracking or an aspect thereof herein, such as a feed, a product gas, a reactor, a furnace, a radiant zone, or a convection zone, this also may refer to a more general conversion reaction and vice versa.

[0009] Said preheating and said cooling, as proposed herein, comprises transferring heat from said product gas or a part thereof to said reaction feed or a part thereof using a thermal energy recovery assembly comprising one or more inner passages and one or more outer passages coaxially surrounding the inner passage(s), an outer passage also being referred to with terms such as "annulus," "annular space," etc., herein. The thermal energy recovery assembly may, in embdodiments, comprise one or more heat transfer enhancement structures to enhance heat transfer from the inner passage(s) to the outer passage(s). Reference is made to the explanations below. Said preheating and said cooling also comprises passing said reaction feed or said part thereof through said outer passage(s) of the thermal energy recovery assembly and said product gas or said part thereof through said inner passage(s) of the thermal energy recovery assembly. The term "passage(s)" is used herein as a shorthand form of "one or more passages" and "at least one passage." The term "passage," furthermore, may relate to any kind of space which is adapted to pass a fluid through the thermal energy heat recovery assembly. In its simplest form, a passage may be provided as a straight tube, but, as further explained below, it may also include inner structures or be provided as multiple tubes in embodiments disclosed herein.

[0010] Said firing the reactor comprises providing an oxidator gas at an oxidator gas temperature level of more than 400 °C using an oxidator gas preheating system and combusting a fuel gas comprising hydrogen using said oxidator gas at the fuel gas temperature level. The fuel gas may, in examples, be pure hydrogen or a mix of hydrogen with ammonia or methane. Alternatively, the fuel gas may comprise any hydrocarbons additionally or alternatively to hydrogen.

The term "oxidator gas," as used herein, shall refer to any gas or gas mixture comprising oxygen, such as pure or essentially pure oxygen, technical grade oxygen, oxygen enriched air or atmospheric air. The oxidator gas temperature level may particularly reach values of up to 500, 600, 700, or 800 °C, and the oxidator gas is, at least in part using the oxidator gas preheating system, heated up to such temperatures.

[0011] In the method as provided herein, said thermal energy recovery assembly is configured to meet a set of operation constraints which are particularly predefined and which include a first temperature constraint for an outside temperature of a containment of said inner passage of said thermal energy recovery assembly and a second temperature constraint for an inside temperature of said containment of said inner passage of said thermal energy recovery assembly.

[0012] Said "outside temperature" of the containment of the inner passage is particularly a temperature of a material surface facing to the reaction feed during the latter is passed through the outer passage(s), and said "inside temperature" of the containment of the inner passage is particularly the temperature of a material surface facing towards the product gas while the latter is passed through the inner passage(s). Said temperatures are therefore particularly temperatures of one or more walls dividing the inner passage(s) from the outer passage(s). A "containment" may particularly be a shaped metal sheet, a tube wall, or any other structure separating the inner passage(s) and the outer passage(s) from each other.

[0013] Particularly, said first temperature constraint limits said outside temperature to a first temperature range. Said second temperature constraint particularly limits said inside temperature to a second temperature range. Using the method provided herein, and embodiments thereof, the thermal energy recovery is advantageously performed such as to operate within advantageous operating regimes, particularly essentially without performance loss which might occur through unwanted and disadvantageous feed pre-cracking and/or effluent coking.

[0014] As found by the present inventors, the heat duty of the feed reaction preheating in the heat recovery assembly matches the heat duty needed in the convection zone for high, but, from a technical perspective, still reasonable oxidant preheating, Therefore, particularly a combination of the aspects proposed herein has a synergistic effect going beyond a mere accumulation of advantages.

[0015] In embodiments as disclosed herein, the first temperature range is selected, particularly depending on a type of said reaction feed, between 550 and 750 °C. This advantageously allows preventing pre-cracking in the reaction feed in the outer passage(s) or annular side(s) of said thermal energy recovery assembly. An upper limit of this first temperature range may particularly be defined by the risk of pre-cracking initiation in the outer passage(s) which is dependent on the reaction feedstock type. Particularly for an ethane type feedstock this upper temperature limit may be 700 to 720 °C. Particularly for a propane type feedstock this upper temperature limit may be 680 to 700 °C. Particularly for a butane type feedstock this upper temperature limit may be 660 to 680 °C. Particularly for a naphtha type feedstock this upper temperature limit may be 640 to 660 °C. Particularly for feedstocks heavier than naphtha this upper temperature limit may be 540 to 600 °C. A feedstock of a certain "type," in the understanding used herein, may contain or consist of the characterizing compounds or compound class (ethane, propane, butane, etc.) in an amount of at least 50, 60, 70, 80, 90 or 95% by volume, mass or on a molar basis.

[0016] According to some embodiments, the second temperature range is selected, particularly depending on a type of the reaction feed. The lower temperature limit between 150 and 350 °C is advantageously preventing condensation coking on the cracked gas side in the inner passage(s) of said thermal energy recovery assembly. The upper temperature limit for the second temperature range may be defined by the risk of enhanced chemical coking at the inner passage(s) inside surface and may be determined by the effluent reactivity at temperatures above 650 to 680 °C. The lower temperature limit may be defined by expected coking reactions due to the condensation of heavy components of the effluents and may be determined by the feed type and the cracking conditions. Particularly for an ethane type feedstock, the lower temperature limit may be 180 to 220 °C. Particularly for a propane type feedstock, the lower temperature limit may be 200 to 250 °C. Particularly for a butane type feedstock, the lower temperature limit may be 230 to 270 °C. Particularly for a naphtha type feedstock or feedstocks heavier than naphtha (in terms of boiling range), the lower temperature limit may be 280 to 320 °C.

[0017] In certain embodiments, said thermal energy recovery assembly comprises one heat recovery stage or several heat recovery stages arranged in parallel or in series, wherein each of the heat recovery stages is either provided in a countercurrent flow configuration or a cocurrent flow configuration, wherein in said countercurrent flow configuration said product gas or said part thereof and said reaction feed or said part thereof are passed in opposite directions through the heat recovery stage and in said cocurrent flow configuration said product gas or said part thereof and said reaction feed or said part thereof are passed in the same direction through the heat recovery stage. This allows for a selective adjustment in the heat transfer properties in each stage. Herein, the term "stage" is used to refer to a distinct heat transfer section or unit which may generally be provided independently from another heat transfer section or unit, wherein particularly at least one of the mediums passed through one of the heat transfer sections is independently controllable from another.

[0018] According to an embodiment, said product gas or said part thereof is passed through one of said heat recovery stages in said cocurrent configuration before being further cooled, e.g. in a different one of said heat recovery stages.

This has the particularly advantageous effect of rapidly cooling said product gas in order to essentially immediately stop cracking reactions.

[0019] Furthermore, in such an embodiment, downstream of said heat recovery stage in cocurrent configuration said product gas or said part thereof may be passed through one of said heat recovery stages which is provided in said countercurrent flow configuration. In other words, said different one of said heat recovery stages is in countercurrent flow configuration. This embodiment allows for a particularly effective cooling and utilization of heat at a comparatively low heat level.

[0020] In such an embodiment, the product gas may be passed through a steam generating thermal energy recovery assembly before being cooled in said heat recovery stage provided in said countercurrent configuration. That is, the steam generating thermal energy recovery stage may be a first stage of the thermal energy recovery assembly, followed by a second stage of the thermal energy recovery assembly. The second stage may be in counter-or cocurrent configuration or a combination thereof.

[0021] The steam generating stage may also be a separate apparatus apart from the thermal energy recovery assembly. This allows for generating steam in an amount adapted to what is needed in the method.

[0022] Any embodiment of the thermal energy recovery assembly may be extended downstream by an additional and separate steam generating device. That is, alternatively or additionally to providing a downstream countercurrent heat recovery stage of said thermal energy recovery assembly, a separate thermal energy recovery assembly may be provided, particularly as a tube-in-tube or shell-and-tube type heat exchanger and particularly in a countercurrent configuration as explained above.

[0023] In embodiments, downstream of a cocurrent heat recovery stage, the product gas may be further cooled in a cocurrent stage heat recovery configuration by partially or fully vaporizing a reaction feed and diluent steam mix at least partially used in forming the reaction feed according to certain embodiments. This is a particularly advantageous way to utilize heat at a lower temperature level.

[0024] According to some embodiments, cooling said product gas or said part thereof is performed at a rate of at least 2.5 K/ms (Kelvins per millisecond), at least 3.5 K/ms, or at least 4.5 K/ms, particularly at hot reactor effluent temperature levels, i.e. temperature levels of the product gas, above 600 °C.

[0025] A pressure drop of said product gas or said part thereof passing through said thermal energy recovery assembly may, in such a configuration, be less than 0.35 bar, less than 0.30 bar, less than 0.25 bar, less than 0.20 bar, or less than 0.15 bar.

[0026] A residence time of said product gas or said part thereof within the thermal energy recovery assembly may less than 100 ms (milliseconds), less than 95 ms, less than 90 ms, less than 85 ms, less than 83 milliseconds, or less than 80 ms at hot reactor effluent temperature levels above 600 °C.

[0027] A pressure drop of said reaction feed or said part thereof passing through said thermal energy recovery assembly may be from 2 to 15 bar, from 2.5 to 10 bar, from 3 to 8 bar, from 3 to 10 bar, from 4 to 9 bar, or from 5 to 8 bar.

[0028] In the method proposed herein, oxidant preheating in the oxidant preheating system may comprise a first heating step indirectly against heat of the product mixture using an intermediate heat carrier, e.g. hot boiler feed water heated in a quench heat exchanger or e.g. saturated high-pressure steam raised in a quench exchanger, particularly in a temperature range of 180 to 300 °C, and at least a further oxidant preheating step comprising heating of the oxidant against hot flue gas in the convection zone of the reactor, particularly in a temperature range of 300 to 800 °C.

[0029] A thermal energy recovery assembly for use in a method according to any embodiment disclosed herein, i.e., for use in a method to produce olefins comprising preheating a reaction feed, firing a conversion reactor, subjecting the reaction feed to a conversion in the conversion reactor, withdrawing a product gas from the conversion reactor, and cooling the product gas withdrawn from the conversion reactor, is also proposed.

[0030] Furthermore, an apparatus for producing olefins, particularly adapted to perform a steam cracking process, and including such a thermal energy recovery assembly is proposed herein. The apparatus is particularly adapted to preheat a reaction feed, to fire a conversion reactor, to subject the reaction feed to a conversion in the conversion reactor, to withdraw a product gas from the conversion reactor, and to cool the product gas withdrawn from the conversion reactor. The apparatus particularly comprises correspondingly configured apparatus sections, devices, etc.

[0031] Hereinbelow, the thermal energy recovery assembly and the apparatus and embodiments thereof are described, where explanations relating to the thermal energy recovery assembly likewise relate to the apparatus and vice versa.

[0032] Said thermal energy recovery assembly particularly is adapted to perform at least a part of said preheating and said cooling by transferring heat from said product gas or a part thereof to said reaction feed or a part thereof, and said thermal energy recovery assembly comprises one or more inner passages and one or more outer passages coaxially surrounding said inner passage(s).

[0033] The thermal energy recovery assembly as proposed therein is particularly adapted to perform said preheating and said cooling as to further comprise passing said reaction feed or said part thereof through said outer passage(s) of said thermal energy recovery assembly and passing said product gas or said part thereof through said inner passage(s) of said thermal energy recovery assembly.

[0034] The apparatus is particularly configured to perform said firing the reactor to comprise providing an oxidator gas at an oxidator gas temperature level of more than 400 °C using an oxidator gas preheating system and combusting a fuel gas comprising hydrogen using said oxidator gas at the fuel gas temperature level. Said oxidator gas preheating system is also provided according to an embodiment.

[0035] Said apparatus and/or said thermal energy recovery assembly is configured to meet a set of operating constraints including a first temperature constraint relating to an outside temperature of said inner passage of said thermal energy recovery assembly and a second temperature constraint relating to inside temperature of said inner passage of said thermal energy recovery assembly. A corresponding control unit adapted to perform said operation may be provided, even if, in some embodiments, the constraints proposed herein may be reached by design choices of the thermal energy recovery assembly. In both alternatives, the thermal energy recovery assembly is configured to meet said set of operating constraints.

[0036] Control measures governed by a corresponding control unit may include flow-controlled bypasses around single and/or multiple stages of the thermal energy recovery assembly and/or around bundles in the convection section of the conversion reactor. Such bypass control could be used e.g. to lower the reaction feed inlet temperature to some stages, if necessary in some operating conditions. Bypasses may be provided, according to some embodiments, particularly in the reaction feed preheating sequence and/or in the oxidator gas preheating sequence.

[0037] Measurement inputs to control units provided according to embodiments proposed herein may be flow rate and temperature measurements at inlets/outlets of heat exchangers or stages of the thermal energy recovery assembly, which can be used for model-based calculations of the tube metal temperature profile using the design information of the actual exchangers.

[0038] As additional measures, in some embodiments, electric preheaters in the feed preheating sequence and/or in the air preheating sequence may be provided. The power input to the preheaters may be adjusted during operation to stay within the temperature constraints in the thermal energy recovery assembly.

[0039] Moreover, the final oxidatorgas preheating temperature may also be varied during operation (e.g. by using such bypasses), according to embodiments as proposed herein, thereby modifying the temperature profile in the convection section, and thus the feed preheating steps in the latter.

[0040] Alternatively to using a control unit, an apparatus provided in embodiments of the present disclosure may specifically be designed to avoid an operation in critical temperature areas. The whole quench process, the thermal energy recovery assembly and the conversion reactor arrangement may be specifically designed to avoid this.

[0041] According to the present disclosure, the thermal energy recovery assembly may comprise one or more heat transfer enhancement structures, as mentioned, to enhance heat transfer from the inner passage to the outer passage. Embodiments of the present disclosure, which will now be described in more detail, relate to specific configurations of such heat transfer enhancement structures.

[0042] The heat transfer enhancement structure(s) may, in embodiments proposed herein, be provided as, or including, at least one of an impingement structure, a turbulence promotion structure, a high-shear-inducing structure, or an increased surface area. The outer passage(s) may particularly comprise a first stage which may be equipped with such structures. That is, in embodiments, said heat transfer enhancement structure(s) is or are provided as, or include(s), at least one of an impingement structure, a turbulence promotion structure, a high-shear-inducing structure, and an increased surface area, and said heat transfer enhancement structure(s) is or are provided in the outer passage(s) of the thermal energy recovery assembly and/or in at least one heat recovery stage thereof.

[0043] In an embodiment as provided herein, the outer passage of the thermal energy recovery assembly comprises a plate impingement between an upstream end and a downstream end, the plate impingement comprising a first channel having a stage inlet at an upstream end and being closed to flow at the downstream end, a second channel having a stage outlet at the downstream end, the second channel being disposed between the first channel and the inner passage, a wall separating the first channel from the second channel, the wall defining openings to fluidly connect the first channel and the second channel, and the plate impingement being configured to receive reaction feed through the stage inlet, pass reaction feed from the first channel to the second channel via the openings of the wall, and cause the flow of the reaction feed to impinge onto an outer surface of the inner passage and exhaust reaction feed through the stage outlet of the second channel. The openings in the wall may particularly provided by regular or irregular perforations of the wall.

[0044] In some embodimemts as provided herein, furthermore, on the thermal energy recovery assembly the outer passage comprises a piccolo impingement, the piccolo impingement comprising an upstream divider disposed about the inner passage and within the outer passage, a downstream divider disposed about the inner passage and within the outer passage downstream of the upstream divider within the outer passage, the downstream divider defining at least one stage outlet, a chamber defined within the outer passage and about the inner passage between the upstream divider and the downstream divider and piccolo passages offset from the inner passage, the piccolo passages extending through the chamber from the upstream divider to the downstream divider, the piccolo passages including a stage inlet for receiving incoming feed, the piccolo passages including a plurality of openings defined therein, the piccolo impingement being configured to receive feed from the stage inlets, flow feed from the piccolo passages into the chamber via the plurality of openings, and exhaust feed from the chamber via the at least one stage outlet.

[0045] In the thermal energy recovery assembly, the outer passage may comprise at least a first stage and a second stage, wherein the first stage and the second stage are in series, and both stages comprise at least one heat transfer enhancement structure.

[0046] In embodiments, the passage of the thermal energy recovery assembly comprises a heat transfer enhancement structure comprising at least one of a turbulence promotion structure, a high-shear-inducing geometry, and an increased surface area.

[0047] According to certain embodiments, the thermal energy recovery assembly may comprise a plurality of inner passages parallel with one another, wherein each inner passage may be disposed within an outer passage and each outer passage may comprise at least one of an impingement structure, a turbulence promotion structure, a high-shear-inducing geometry, an increased surface area to enhance heat transfer from the inner passage to the outer passage.

[0048] Still other aspects and advantages of the exemplary embodiments summarized above and other embodiments, are discussed in detail herein. Moreover, it is to be understood that both the foregoing information and the following detailed description provide merely illustrative examples of various aspects and embodiments, and are intended to provide an overview or framework for understanding the nature and character of the claimed aspects and embodiments. Accordingly, these and other objects, along with advantages and features of the present disclosure, will become apparent through reference to the following description and the accompanying drawings. Furthermore, it is to be understood that the features of the various embodiments described herein are not mutually exclusive and may exist in various combinations and permutations.

BRIEF DESCRIPTION OF THE DRAWINGS

[0049] The accompanying drawings, which are included to provide a further understanding of the embodiments of the present disclosure, are incorporated in and constitute a part of this specification, illustrate embodiments of the present disclosure, and, together with the detailed description, serve to explain principles of embodiments discussed herein. No attempt is made to show structural details of this disclosure in more detail than may be necessary for a fundamental understanding of the embodiments discussed herein and the various ways in which they may be practiced. According to common practice, the various features of the drawings discussed below are not necessarily drawn to scale. Dimensions of various features and elements in the drawings may be expanded or reduced to more clearly illustrate embodiments of the present disclosure.

FIGS. 1A to 1F are schematic views of highly-efficient, low-emission fired furnace assemblies in combination with thermal heat recovery assemblies for the hot reactor effluent in accordance with embodiments of the present disclosure.

FIG. 2A is a partial schematic section side view of an example thermal energy recovery assembly according to embodiments of the present disclosure.

FIG. 2B is a partial schematic section end view taken along line B-B of the example assembly shown in FIG. 2A according to embodiments of the present disclosure.

FIG. 3A is a partial schematic perspective view of another example thermal energy recovery assembly according to embodiments of the present disclosure.

FIG. 3B is a partial schematic section end view taken along line B-B of the example assembly shown in FIG. 3A according to embodiments of the present disclosure.

FIG. 4A is a schematic section view of an example inner passage including example rounded projections on an interior surface according to embodiments of the disclosure.

FIG. 4B is a schematic section view of an example inner passage including rectangular projections on an interior surface according to embodiments of the disclosure.

FIG. 5 is a block diagram of an example method to produce olefins according to embodiments of the present disclosure.

FIG. 6 to 11 are schematic configurations for possible flow routing on hot reactor effluent side and on the feed side in a single or two-stage thermal energy recovery assembly according to embodiments of the present disclosure.

DETAILED DESCRIPTION

[0050] The drawings include like numerals to indicate like parts throughout the several views, the following description is provided as an enabling teaching of exemplary embodiments, and those skilled in the relevant art will recognize that many changes may be made to the embodiments described. It also will be apparent that some of the desired benefits of the embodiments described may be obtained by selecting some of the features of the embodiments without utilizing other features. Accordingly, those skilled in the art will recognize that many modifications and adaptations to the embodiments described are possible and may even be desirable in certain circumstances. Thus, the following description is provided as illustrative of the principles of the embodiments and not in limitation thereof.

[0051] The phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. As used herein, the term "plurality" refers to two or more items or components. The terms "comprising," "including," "carrying," "having," "containing," and "involving," whether in the written description or the claims and the like, are open-ended terms, i.e., to mean "including but not limited to," unless otherwise stated. Thus, the use of such terms is meant to encompass the items listed thereafter, and equivalents thereof, as well as additional items. The transitional phrases "consisting of" and "consisting essentially of," are closed or semi-closed transitional phrases, respectively, with respect to any claims. Use of ordinal terms such as "first," "second," "third," and the like in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish claim elements.

[0052] In addition, while reference may be made herein to quantitative measures, values, geometric relationships or the like, unless otherwise stated, any one or more if not all of these may be absolute or approximate to account for acceptable variations that may occur, such as those due to manufacturing or engineering tolerances or the like.

[0053] FIGS. 1A to 1F schematically illustrate concepts of highly efficient and low-emission gas fired furnace assemblies, combined with a thermal energy recovery assembly, and combined with oxidant preheating, i.e. apparatus in accordance with embodiments of the present disclosure. In some embodiments, the gas fired furnace assembly may be used for producing olefins from reaction feedstock, such as for example, ethane, propane, butane, condensate, light naphtha, heavy naphtha, gas oil, pyrolysis oil, materials derived from processing refinery streams, Fischer-Tropsch products, plastic waste, and/or biofeedstocks.

[0054] Before turning to features and advantages of the apparatus provided according to the present disclosure, some features of conventional apparatus will be referred to on the basis of FIGS. 1A to 1F, and the advantage solutions provided herein will be explained.

[0055] In a conventional gas-fired olefins production furnace or conversion reactor, combustion can only supply heat to the cracking reaction when the temperature exceeds the temperature of reaction, for example, from 550 or 650 °C to 850 °C. In the understanding used herein, a gas-fired olefins production furnace is selected as one type of conversion reactor which may be used according to the present disclosure, and the more general terms "reaction feed," "conversion reactor," and "product gas" are used for a cracking feed, a cracking furnace, and a cracked or raw gas.

[0056] Heating to exceed the reaction temperature is performed in the so-called radiant zone or section which is indicated with reference numeral 10 in FIGS. 1A to 1F. Once the fuel gases or flue gases have cooled below this temperature in the radiant zone 10, there may be a desire to extract as much of the remaining heat as possible to achieve energy-efficient operation. This heat is recovered in a so-called convection zone or section which is extends downstream of the position of reference numeral 9 in FIGS. 1A to 1F. The radiant zone 10 and the convection zone 9 are often commonly referred to as "furnace." Often the remaining energy is used to preheat the reactor feeds and diluent steam in the convection zone 9 to the temperature needed for the cracking reaction to occur, as further explained in detail below.

[0057] In olefin production, once the feed is cracked, the reactor effluent should be cooled before further processing of the cracked gas. Ideally, the initial cooling occurs quickly to reduce or prevent side reactions in the reactor effluent while it is still at relatively high temperatures. In addition, for an energy-efficient process, the heat of the reactor effluent should be recovered to the greatest extent possible and technically or economically feasible to be used elsewhere in the process.

[0058] In some systems, this quenching and cooling takes place in so-called transfer line exchangers (TLE), where the reactor effluent is cooled by exchanging heat with liquid water to produce high-pressure steam. Cooling by exchanging heat with boiling water has the advantage that heat transfer is generally more rapid than when cooling against a gas, sometimes five or even ten times faster for the same exchanger geometry. This steam may be used to power steam turbines or other auxiliaries.

[0059] For example, the steam is commonly used to power a cracked gas compressor, one or more refrigeration compressors, or one or more pumps. The use of steam to drive rotating equipment such as compressors and pumps is a convenient way to use the energy recovered from cooling the reactor effluent, but the efficiency of converting energy in the form of heat (e.g., the heat contained in steam) to mechanical work is typically low and in the range of 30 to 50% only.

[0060] One solution to reducing the large amount of carbon dioxide produced by conventional steam cracking processes would be to reduce the furnace's fired duty by recycling as much as possible of the remaining heat of combustion, which cannot be used for the cracking reaction, back to the radiant zone. This can be realized by preheating the oxidant externally of the convection zone and/or internally of the convection zone against hot flue gas. Fired steam cracking furnaces with high levels of oxidant preheating have reduced emissions as compared to conventional gas-fired cracking furnaces without oxidant preheating. The cracking furnace emissions can be further reduced when oxidant preheating is combined with combustion of pure hydrogen or fuel gas mixtures comprising hydrogen. Further cracking furnace emission reduction is possible with additional fuel gas preheating.

[0061] However, those low-emission and at the same time highly efficient steam cracking furnaces introduce new technical challenges that must be overcome. One consequence of using hot flue gas for oxidant preheating in a fired cracking furnace is the lack of heat for heating the feed and diluent steam, so that heating of these must be supplied by other means. A second consequence is the need for different energy integration within the cracking process. Rotating equipment such as compressors and pumps are easily powered by electricity. Moreover, the efficiency of operation of such equipment with electricity is much higher than with steam, with energy efficiencies of greater than 90% commonly achieved when using electricity as compared to 30 to 50% typically obtained when using steam. Therefore, in a highly efficient steam cracking process there is considerable incentive to power these devices using electricity. This means that the energy currently recovered when cooling the reactor effluent can no longer be used for powering pumps and compressors. Instead there is a need to find a different use for this energy so that the overall energy efficiency of the process can be maintained at a high level. It is particularly such a use which is provided according to embodiments as disclosed herein.

[0062] For a highly efficient and low emission steam cracking process, in the context of the present disclosure a need for systems and methods for convection zone design was identified that also incorporates preheating of an oxidator gas besides other heating services. Furthermore, a need for systems and methods for using the energy obtained from quenching hot reactor effluent while still quenching the cracked gas quickly enough to prevent further reaction and being as reliable as conventional steam raising quench systems was identified, as well as preferred operating windows/regimes to prevent the thermal energy recovery assembly equipment from undesirable performance loss through feed pre-cracking and/or effluent coking mechanisms. Furthermore, a need for systems and methods for preheating a feed at reduced available fuel gas heat in a low-emission fired furnace was identified.

[0063] Solutions to these needs and problems have already been summarized above and will be explained in more detail hereinbelow.

[0064] As mentioned in other words above, the proposed method includes preheating a reaction feed, i.e. particularly a reaction feed with or without steam, in a thermal energy recovery assembly to produce a preheated reaction feed, and supplying the preheated reaction feed to a highly efficient and low emission gas-fired conversion reactor. Said conversion reactor may particularly be a cracking furnace comprising a reaction or radiant zone 9 wherein the preheated reaction feed is heated and converted, particularly by steam cracking, to output a hot reactor effluent comprising cracked hydrocarbons, i.e. olefins, and unconverted hydrocarbons. The reactor effluent is also referred to as a "product gas" herein, as already mentioned. A preheated oxidant or oxidator gas is combusted for heating the conversion reactor or its reaction zone. The hot reactor effluent or product gas is cooled in the thermal energy recovery assembly, by transferring heat to the reaction feed. The proposed method includes advantageously configuring the thermal energy recovery such to operate within preferred operating regimes without performance loss through feed pre-cracking and/or effluent coking, as already mentioned above.

[0065] As mentioned, in the thermal heat recovery assembly one or more stages may be provided in series or parallel configuration, with each of them having either countercurrent or cocurrent flow direction. Combinations of cocurrent and countercurrecnt configurations may also be provided. The detailed layout of these stages in terms of the layout or the inner and outer passages as well as heat transfer enhancement methods and structures may differ in parts or entirely.

[0066] In certain embodiments of the thermal heat recovery assembly, the individual stages are configured and sized such, that the thermal energy recovery operates within operating regimes without performance losses. The latter may occur when through chemical and/or physical processes fouling layers are generated on the inner passage's inside or inner passage's outside surfaces (i.e. the surfaces of the containment of the inner passage as explained above) reducing the heat transfer from the inner passage to the outer passage. Beside the type and composition of the reaction feed and the composition of the product gas, these chemical and physical processes heavily depend on the temperature prevailing on the inner and outer surfaces of the inner passage or its containment.

[0067] Such kind of processes are feed pre-cracking in the outer passage and chemically and physically induced coking in the inner passage. Feed pre-cracking in the outer passage defines an upper temperature level, which shall not be exceeded on the inner passage outside surface. An additional upper temperature level, which shall not be exceeded on the inner passage inside surface, is defined by accelerated chemical coking at high surface temperature. A lower temperature level, which shall not be undercut on the inner passage inside surface, is defined by coking driven by the condensation of heavy components in the effluent. Specific temperature ranges were already given above.

[0068] In an embodiment 100 illustrated in FIG. 1A, liquid feedstock 21, e.g. naphtha, is preheated and partially vaporized in a primary feed preheater convection bank 1. A convection bank is, in the understanding herein, an arrangement of one or more heat recovery structures or bundles in the convection zone 9 of a corresponding furnace or reactor. The partially vaporized naphtha 22 is then mixed with superheated diluent steam using a mixing nozzle 20. Said diluent steam may be provided from steam 30 superheated in a separate heat exchanger unit, a primary diluent steam superheater 44, against saturated very high-pressure steam (the term "very high-pressure steam" or VHP steam indicates steam at a pressure level of 100 to 130 bar) and then further superheated in convection zone 9 in a secondary diluent steam superheater 4 against flue gas. The mix of feed and diluent steam is then further superheated in a secondary feed preheater convection bank 3. It is then fed, as indicated with 23, to a countercurrent flow stage 13 of a thermal energy recovery assembly 110 where it is heated against prequenched hot reactor effluent or product gas that has passed already through a part 12 of the thermal energy recovery assembly 110.

[0069] A reaction feed 24 leaves the stage 13 of the thermal energy recovery assembly 110 at a hot end and is routed to a hot end of a cocurrent flow stage 12 where it is further heated against hot reactor effluent or product gas 27 coming from cracking coils 11 in the radiant section 10. Other configurations of a thermal energy recovery assembly 110, such as shown in Figures 6 to 10, are possible as well for this embodiment 100 and the further embodiments shown in FIGS. 1B to 1F below. After having been heated in both stages 12, 13 of the thermal energy recovery assembly 110, the feed 25 is transferred to a high temperature coil 8 in a convection section 9 of the fired furnace, where it is heated close to the cracking temperature, now being indicated 26, and then transferred to a cracking coil 11. The reaction feed is then cracked in the coil 11 to provide a hot reactor effluent or product gas 27 including the desired products.

[0070] The heat for the cracking reaction is supplied by combustion of pure hydrogen or a hydrogen containing fuel gas 41 together with preheated oxidant or oxidator gas 36 in the radiant zone 10. To provide preheated oxidator gas 36, unheated oxidator gas 32 is provided and preheating is realized in two steps: A oxidant blower 18 supplies oxidant to an external primary oxidant preheater 17, where the oxidator gas 32 is heated against saturated high-pressure steam supplied by a steam drum 15. The oxidator gas, now indicated 35, is then routed to a secondary oxidant preheater convection bank 7 in the convection zone 9 of the fired cracking furnace and supplied for combustion to the burners in the radiant zone 10. In some embodiments, the secondary oxidant preheater 7 may comprise multiple bundles, arranged in series and vertically on top of each other in the convection zone as generally known in the field.

[0071] Steam from steam drum 15 is raised in a secondary quench exchanger device 14, which further cools down prequenched hot reactor effluent or product gas 28 coming from the thermal energy recovery assembly 12 and 13. Saturated steam 38 from the steam drum 15 is utilized for heating purposes (heaters 17, 42, 43, 44) and parts of the saturated steam from the steam drum 15 is routed to steam superheating convection banks 5 and 6, with a nozzle in between, where boiler feed water 31 is injected for temperature conditioning of the superheated steam 40. Superheaters 42, 43 shown in hatched form can be considered as process alternatives to heat exchanger 44 or additional heaters, e.g. for heavy feedstocks with high boiling temperatures such as heavy naphtha or atmospheric gasoil.

[0072] Hot condensate 33 from the heaters 17, 42, 43, 44 is routed back to the steam drum 15 and, thus, reduces the required amount of make-up boiler feed water 37. High combustion temperatures in the radiant zone 10 due to oxidant preheating and/or hydrogen firing can lead to increased nitrous oxide (NOx) content in the flue gas. Thus, a selective catalytic reduction unit, hereinafter referred to as DeNOx unit, might be advantageous to reduce NOx emissions to atmosphere. The DeNOx unit 2 requires a specific flue gas temperature window for effective NOx removal and is therefore installed in the convection section 9 between the heat recovery banks 1 and 3 in the present embodiment and part of the flue gas may be recycled upstream thereof.

[0073] Further elements shown in Figure 1A include a flue gas blower 19 with which flue gas, indicated with 34, is withdrawn from the convection zone 9. Product gas 27 downstream of the thermal energy recovery assembly 12 and 13 is indicated with 28 and the product gas 28 downstream of the heat exchanger 14 is indicated with 29.

[0074] In some embodiments, the convection section of the fired furnace may not require the high temperature coil 8 in the convection section 9, as displayed in FIG. 1B for an embodiment 200. Heated feed 25 from the thermal energy recovery assembly 110 is, in this embodiment, directly routed to the cracking coils 11 for cracking of the hydrocarbons contained therein. This allows for even higher temperature levels of oxidant preheating in the secondary oxidant preheater 7.

[0075] In an embodiment 300 shown in FIG. 1C, more heat is transferred from hot reactor effluent to the feed stream than in the embodiment 100 of FIG. 1A. This enables higher levels of oxidant preheating in a split primary and secondary high temperature oxidant preheater convection bank 6 and 8, with a high temperature coil 7 located in between.

[0076] In an embodiment 400 shown in FIG. 1D, gaseous feedstock 21, e.g. ethane, is preheated in the primary feed preheater convection bank 1. It is then mixed with diluent steam 30 in a mixing nozzle 20. The mix 23 of feed and diluent steam is then fed to a countercurrent flow stage 13 of the thermal energy recovery assembly 110 where it is heated against pre-quenched hot reactor effluent or product gas 27 that has passed already through part 12 of the thermal energy recovery assembly 110. The feed 23, now indicated 24, leaves the stage 13 of the thermal energy recovery assembly 110 at the hot end and is routed to the hot end of a cocurrent flow stage 12 thereof, where it is further heated against hot reactor effluent or product gas 27 coming from the cracking coils 11. After being heated in both stages of the thermal energy recovery assembly 110, the feed, now indicated 25, is transferred to a high temperature coil 7 in the convection section of the fired furnace, where it is heated close to the cracking temperature, and then, now indicated 26, transferred to the cracking coil 11.

[0077] The reaction feed is then cracked in the coil to provide hot reactor effluent or product gas 27 including the desired products. The heat for the cracking reaction is supplied by combustion of hydrogen or a hydrogen containing fuel gas 36 together with the preheated oxidant or oxidator gas 41 in the radiant zone 10. To provide preheated oxidator gas 41, unheated oxidator gas 32 is provided and preheating is realized in two steps: A oxidant blower 18 supplies the oxidant to an external primary oxidant preheater 17, where the oxidant is heated against hot boiler feed water 37. The oxidant, now indicated 35, is then routed to the secondary oxidant preheater convection bank 6 in the convection zone 9 and then heated in a third step in a ternary oxidant preheater convection bank 8 of the convection zone 9 of the fired cracking furnace and is finally supplied for combustion to the burners in the radiant zone 10. In some embodiments, the secondary and ternary oxidant preheaters 6 and 8 may comprise multiple bundles, arranged in series and vertically on top of each other in the convection zone 9.

[0078] The steam from steam drum 15, which also can be high pressure steam at 60 to 80 bar or very high pressure steam at 100 to 130 bar, is raised in a secondary quench exchanger device 14, which further cools down pre-quenched hot reactor effluent or product gas 28 coming from the thermal energy recovery assembly 110. The saturated steam 38 from the steam drum 15 is routed to the steam superheating convection banks 4 and 5, with a temperature conditioning nozzle in between (not specifically illustrated), where boiler feed water 31 is injected. In this embodiment, boiler feed water serves as a heat carrier to transfer heat from the cracked gas to the oxidant preheating: Boiler feed water 37 is heated in a ternary quench cooler 14a against pre-quenched cracked gas 28 and then cooled in a second step in the primary oxidant preheater 17. The cooled boiler feed water is then fed to an economizer convection bank 2 in the convection section 9 before it is routed to the steam drum 15.

[0079] High combustion temperatures in the radiant zone 10 due to the high levels of oxidant preheating and/or hydrogen firing can lead to increased NOx content in the flue gas. Thus, a DeNOx unit, might be required to reduce NOx emissions to atmosphere. The DeNOx unit 3 requires a specific flue gas temperature window for effective NOx removal and is therefore installed in the convection section 9 between the heat recovery banks 2 and 4 in the present embodiment.

[0080] In some embodiments 500 for gaseous feedstock according to FIG. 1E, the heated boiler feed water 37 may be used to preheat not only the oxidant for the combustion but, using a side stream 51, also the fuel 36 in a parallel fuel preheater 50.

[0081] In some embodiments 600 according to FIG. 1F, in particular for heavy reaction feedstock such as atmospheric gasoil, the preheated feed 22 from primary feed preheater 1 may be mixed with process steam 30 in a first mixing nozzle, 20a and then routed to a cocurrent flow stage 13 of the thermal energy recovery assembly 110 where it is partially or fully vaporized against pre-quenched hot reactor effluent 27 that has passed already through part 12 of the thermal energy recovery assembly. The stream 24 is then routed to a second mixing nozzle 20b, where it is mixed with superheated diluent steam 30 that comes from the diluent steam superheater convection bank 3. Any residual liquid phase in 24 is vaporized by flash vaporization in 20b and routed in a gaseous state to a cocurrent flow stage 13 of the thermal energy recovery assembly, where it is further superheated against hot reactor effluent. The feed 26 may either be fed directly to the cracking coil 11, or further be preheated in a high temperature coil 7 to form feed stream 27. Oxidant preheating and steam superheating may be essentially analogous to the embodiment 100 shown in FIG. 1A.

[0082] As used herein, the phrases "product gas" and "hot reactor effluent" synonymously refer to reactor effluent that is downstream of the cracking coil 11 of the fired furnace 100 in FIGS. 1A to 1F and is being cooled from the temperature at which reactor effluent exited the furnace. In some embodiments, the thermal energy recovery assembly 12 and 13 may include one or more stages, for example, a first stage 12, and a second stage 13, as shown in FIGS. 1A to 1F. In some embodiments including more than one stage, the stages may have substantially the same structural configuration, and in some embodiments including more than one stage, one or more of the stages may have a structural configuration that differs from the structural configuration of other stages. In some embodiments including more than one stage, two or more of the stages may be in series relative to one another (e.g., physically and/or with respect to processing) (see, e.g., FIGS. 1A to 1F), and in some embodiments including more than one stage, two or more of the stages may be in parallel with respect to one another (e.g., physically and/or with respect to processing).

[0083] In some embodiments, the fired furnace may be configured to receive a feed and heat the feed to a reaction temperature to provide a hot reactor effluent. In some embodiments, the feed and/or the effluent may be in the form of a liquid, a gas, or a combination thereof. For example, the reaction furnaces in FIGS. 1A to 1F may be a highly efficient and low emission gas-fired cracking furnace and the feed may be, or include, hydrocarbons for cracking in the furnace to provide a hot reactor effluent including cracked hydrocarbons, for example, in an at least partially gaseous state (e.g., a completely gaseous state). In some embodiments, the furnace may be configured to heat the feed to a cracking temperature to break the hydrocarbons into desired products that may be exhausted from the furnace as a hot reactor effluent. The feed may include, for example, ethane, propane, butane, condensate, light naphtha, heavy naphtha, gas oil, pyrolysis oil, materials derived from processing refinery streams, Fischer-Tropsch products, plastic waste, and/or biofeedstocks. The feed may additionally include steam. In some embodiments, the fired furnace may be configured to receive the feed into one or more reactor zones or reactor chambers (for example, a cracker passage or a cracking coil 11 in FIG. 1A) via a reactor feed line 26 in FIGS. 1A to 1F and exhaust the hot reactor effluent via a reactor effluent line 27 in FIGS. 1A to 1F. In some embodiments, the furnace may be heated via combustion of fuel gas to a cracking temperature, for example, such that the feed substantially continuously flows into the reactor chamber(s) where the coils 11 are arranged via the reactor feed line 26 and out of the reactor chamber(s) as hot reactor effluent via the reactor effluent line 27. The reactor chamber(s) may be heated by radiative and by convective heat transfer of combusted fuel. To increase the efficiency, the feed may be preheated to a temperature closer to the cracking temperature of the feed prior to (e.g., upstream relative to) entering the coils 11.

[0084] The thermal energy recovery assembly 110 in FIGS. 1A to 1F, in some embodiments, may be, or include, a gas-to-gas energy recovery device or heat exchanger. The thermal energy recovery assembly 110may be configured to receive the hot reactor effluent or product gas 27 from the reactor chamber(s) or coils 11 and quench the hot reactor effluent or product gas 27 to a quenched temperature to preserve the desired products within the reactor effluent and/or to prevent side reactions from occurring within the reactor effluent or product gas 27, for example, as the hot reactor effluent or product gas 27 cools. In some embodiments, a single thermal energy recovery assembly 110 may receive hot reactor effluent from multiple reactor chambers or coils 11 therein. In certain embodiments, a single reactor chamber or coils 11 therein may provide hot reactor effluent to multiple thermal energy recovery assemblies 110. The ratio between the number of reactor chambers or coils 11 therein and the number of thermal energy recover assemblies 110 may be, in embodiments, in a range of 0.1 to 10, for example, a range of 0.5 to 2.

[0085] The hot reactor effluent or product gas 27 enters the thermal energy recovery assembly 110 at a temperature of at least 550 °C, at least 575 °C, at least 600 °C, at least 610 °C, at least 620 °C, at least 625 °C, at least 630 °C, at least 640 °C, at least 650 °C, at least 700 °C, at least 750 °C, at least 800 °C, or at least 850 °C. To quench the hot reactor effluent or product gas 27, the thermal energy recovery assembly 110 may utilize the feed as a cooling medium, for example, prior to the feed entering the coils 11 (e.g., upstream of the coils 11). As a result of cooling the hot reactor effluent or product gas 27 within the thermal energy recovery assembly 110, the feed may be preheated to a temperature closer to the cracking temperature thereof (e.g., to a temperature of at least 350 °C, at least 375 °C, at least 400 °C, at least 450 °C, at least 500 °C, or at least 550 °C). As used herein, "quenched reactor effluent" or "quenched product gas" refers to reactor effluent or product gas that has passed through the thermal energy recovery assembly 110. In some embodiments, the hot reactor effluent may additionally be partially cooled or quenched before or after passing through the thermal energy recovery assembly 110. In some embodiments, the preheated feed may be further heated (for example, by means of a high temperature coil in the convection zone 9) before entering the reactor chamber.

[0086] In some embodiments, a thermal energy recovery assembly, which is indicated 1000 in FIG. 2A through FIG. 3B but which may likewise be used in all embodiments shown in Figures 1A through 1F may be configured to recover thermal energy from hot reactor effluent to heat a feed to a highly efficient and low emission gas-fired cracking furnace.

[0087] As explained herein with respect to FIG. 2A through FIG. 3B, in some embodiments, the thermal energy recovery assembly 1000 may include an inner tube or passage 1034 and an outer tube or passage 1040. The inner passage 1034 may include a first inlet that is configured to receive hot reactor effluent from a low-emission gas-fired cracking furnace. The outer passage 1040 may be disposed about the inner passage 1034 to enclose an outer annulus 1044 about the inner passage 1034. Although the terms "outer passage" and "annular" (and derivations from these terms) are used herein, partly or completely synonymous, the "outer annulus 1044" may, or may not, be defined by inner and outer circles to result in an annular cross-section having inner and outer circular boundaries. In some embodiments, the inner and/or outer boundaries of the cross-section may have shapes other than circular, such as triangular, rectangular, polygonal, elliptical, oval-shaped, etc. In some embodiments, the central axis of the inner passage may coincide with the central axis of the outer passage. In some embodiments, the central axis of the inner passage may be offset from the central axis of the outer passage. In consequence, the term "annular" (and derivations thereof) may be interpreted similarly. The outer passage 1044 may include a second inlet that is configured to receive a feed to the highly efficient and low emission gas-fired cracking furnace. The outer passage 1044 may be configured to use the feed for the fired cracking furnace as a cooling medium to recover thermal energy from the hot reactor effluent prior to the feed being supplied to the fired cracking furnace.

[0088] The outer passage 1044 may be configured to enhance heat transfer from the hot reactor effluent to the feed. In some embodiments, hot reactor effluent may reach a first inlet via an effluent gas inlet chamber or other connector. In some embodiments, cooling may be supplied to a feed gas inlet chamber or other connector. In some embodiments, the effluent gas inlet chamber may connect one or more than one reaction chambers to one or more than one inner passage. In some embodiments, a header may be provided to connect the feed to more than one outer passage 1044. In some embodiments, cooled cracked gas from more than one inner passage 1034 may be collected using a header. In some embodiments, heated feed from more than one outer passage 1044 may be combined via a header. In some embodiments, multiple annuli 1044 may be contained in a single mechanical device, which may receive hot effluent from multiple cracking coils via a gas inlet chamber or other connector, and cold feed from a feed header.

[0089] In some applications, the residence time and/or the pressure drop of the reactor effluent in the thermal energy recovery assembly 110 in FIGS. 1A to 1F or 1000 in FIG. 2A through FIG. 3B may be influential on the process and/or the products achieved by the heating process in. Both the residence time and the pressure drop occurring as the hot reactor effluent passes through the thermal energy recovery assembly 110 or 1000 may be influential on ethylene selectivity of products produced by the furnace assembly. The residence time may be defined as the time that the hot reactor effluent exceeds a temperature greater than its cracking temperature, for example, greater than 550 or 650 °C. In some embodiments, both the residence time and the pressure drop may be balanced during the quenching of the hot reactor effluent, for example, to preserve the ethylene selectivity of the reactor effluent. For example, an increased pressure drop in the thermal energy recovery assembly can affect the selectivity as a result of an increased pressure in cracking coils of the furnace assembly which changes selectivity of the cracking reaction in the furnace assembly 100 With respect to residence time, a longer residence time may allow for additional side reactions in the thermal energy recovery assembly 110 or 1000.

[0090] In some embodiments of the present disclosure, the thermal energy recovery assembly 110 or 1000 may be configured to quench the hot reactor effluent or product gas using the reaction feed as a cooling medium for the hot reactor effluent, for example, and such that the feed is preheated by the hot reactor effluent prior to entering the reactor chamber 11. For example, as shown in FIG. 1B, the thermal energy recovery assembly 110 may receive the feed through a cold feed line 23 and provide preheated feed to the reaction chamber 11 through the reactor feed line 26. The thermal energy recovery assembly 12 and 13 may receive hot reactor effluent from the reactor effluent line 27 and provide quenched reactor effluent to a quenched effluent line 28.

[0091] In some embodiments, the thermal energy recovery assembly 12 and 13 in FIGS. 1A to 1F may be configured to operate as a gas-to-gas heat exchanger to exchange heat from the hot reactor effluent to the feed. As a result of heat being exchanged between gases, it is more difficult to quench the reactor effluent within a desired residence time comparable to liquid-to-gas heat exchangers (e.g., steam-generating heat exchangers using boiling water as a relatively low-temperature cooling medium, typically used with gas-fired cracking furnaces), due, for example, to the generally lower heat transfer coefficients in gas-to-gas exchangers and the lower temperature difference between the hot and cold fluids. Therefore, additional design features for thermal energy recovery assembly 110 or 1000 may be desired, as described in some of the exemplary embodiments below.

[0092] With reference to FIG. 2A and FIG. 2B, a portion of an example thermal energy recovery assembly 1000 is shown having a passage-in-passage design with a hot reactor effluent or product gas P flowing through an inner passage 1034 (e.g., a central passage), and the reaction feed F flowing through an outer annulus 1044 at least partially defined by the inner passage 1034 and an outer passage 1040. As shown, the inner passage 1034 is disposed about a central axis of the thermal energy recovery assembly 1000. In some embodiments, the inner passage 1034 may be disposed about the central axis or offset from the central axis of the thermal energy recovery assembly 1000.

[0093] The thermal energy recovery assembly 1000 may be a co current heat exchanger or countercurrent heat exchanger (e.g., as shown) with the hot reactor effluent or product gas P flowing through the thermal energy recovery assembly 1000 in a first direction and the feed F flowing through the thermal energy recovery assembly 1000 in a second direction opposite the first direction. In some embodiments, the inner passage 1034 may include an inlet 1033 and an outlet 1035, with the hot reactor effluent or product gas P entering through the inlet 1033, flowing through the inner passage 1034, and exiting through the outlet 1035. The annulus 1044 may include an inlet 1043 and an outlet 1045, with the reaction feed F entering through the inlet 1043, flowing through the annulus 1044, and exiting through the outlet 1045 as preheated reaction feed F.

[0094] In such embodiments, the hot reactor effluent or product gas P, at its highest temperature prior to being cooled by heat transfer to the reaction feed F to preheat the reaction feed F, enters the thermal energy recovery assembly 1000 at the inlet 1033 at a point adjacent to where the feed, at its highest temperature after being heated by the reactor effluent, exits the thermal energy recovery assembly 1000 through the outlet 1045 as preheated feed. The reactor effluent or product gas P (e.g., a quenched reactor effluent), at its lowest temperature after heating the feed, exits the thermal energy recovery assembly 1000 at the outlet 1035 as quenched reactor effluent at a point adjacent to where the reaction feed F, at its lowest temperature prior to being heated by the hot reactor effluent or product gas P, enters the thermal energy recovery assembly 1000 through the inlet 1043.

[0095] In some such embodiments, the hot reactor effluent or product gas P enters the thermal energy recovery assembly 1000 at its highest temperature at the point where the reaction feed F exits the thermal energy recovery assembly 1000 at its highest temperature, and the reactor effluent or product gas P exits the thermal energy recovery assembly 1000 at its lowest temperature where the feed enters the thermal energy recovery assembly 1000 at its lowest temperature. In some embodiments, the thermal energy recovery assembly 1000 may be a cocurrent heat exchanger with the reactor effluent or product gas P and the reaction feed F flowing in the same direction within the thermal energy recovery assembly 1000. In some embodiments, if the thermal energy recovery assembly 1000 is made up of more than one stage, some stages may be cocurrent and others may be counter current.

[0096] In some embodiments, the inner passage 1034 may be or include a bare or plain tube with a smooth inner surface. In some embodiments, the inner passage 1034 may include heat transfer enhancements or enhancement structures that promote turbulence or increase a surface area of the inner passage 1034. For example, the inner passage 1034 may include velocity rods or other turbulence-promoting structures. In some embodiments, the inner passage 1034 may include fins (for example, straight and/or rifled fins, rectangular and/or rounded in cross-section) or other surfaces to increase a surface area in contact with the reactor effluent or product gas P flowing through the inner passage 1034. Such heat transfer enhancements within the inner passage 1034 may decrease the residence time of the reactor effluent or product gas P. The heat transfer enhancements may increase a pressure drop within the reactor effluent or product gas P. In some embodiments, the inclusion of heat transfer enhancements within the inner passage 1034 may be balanced, for example, to reduce pressure drop that may result from heat transfer enhancements. In certain embodiments, fouling may be expected such that frequent cleaning of the inner passage 1034 may be required. In such embodiments, the inner passage 1034 may be straight or bare to aid in cleaning. In particular embodiments, sections of the inner passage 1034 may be bare, and sections of the inner passage 1034 may include heat transfer enhancements, such as the turbulence-promoting structures and/or the area-increasing features mentioned above.

[0097] In some embodiments, the annulus 1044 may include turbulence-promoting structures, such as, for example, winglets, artificial roughness, washboard/grooves, pin fins, and/or dimples. Such structures may increase the rate of heat transfer from the outer surface of the inner passage 1034, and/or may increase the pressure drop of the reaction feed F traversing the annulus 1044. Such structures may be used by themselves as a heat transfer enhancement structure, or may be used in combination with other heat transfer enhancement structures, such as, for example, the plate and piccolo impingements described herein.

[0098] In some embodiments, the outer annulus 1044 may include a high-shear-inducing geometry configured to promote high-shear flow, for example, as may result from feed flowing at high velocity, such as greater than 50 meters per second (m/s), or greater than 60 m/s, or greater than 70 m/s, or greater than 80 m/s. In some embodiments, the direction of the high-shear feed flow through the outer passage is substantially parallel to the inner passage. In some embodiments, the high-shear-inducing geometry may include configuring the outer passage such that the spacing between the outside surface of the inner passage 34 and the inside surface of the outer passage 40 is 10 millimeters (mm) or less, 8 mm or less, 6 mm or less, or 4 mm or less. The high shear rate may serve as a heat transfer enhancement by promoting a high rate of heat transfer from the reaction feed F to the outside surface of the inner passage 1034.

[0099] In some embodiments, heat transfer enhancement by impingement may refer to flow of fluid passing through the outer passage, whose average direction as it proceeds from inlet to outlet may be substantially parallel to the inner passage, being purposely directed to flow toward the inner passage, for example, using geometric features introduced into the outer passage. In some embodiments, this directed (impinging) flow may, for example, be perpendicular to the inner passage, or directed toward the inner passage at an angle greater than thirty degrees relative to an axis of the inner passage, while its velocity may be relatively greater than a superficial velocity of the outer-passage fluid (for example, the volumetric flow of the outer-passage fluid divided by the area of the annular cross-section between the inner and outer passage). In some embodiments, the geometric features that promote impingement may include, for example, nozzles and/or openings oriented toward the inner passage, and/or obstructions placed in a flow path that may redirect fluid from a direction that is more parallel to the inner passage more directly towards the outer surface of the inner passage. These example features may be implemented in a periodic fashion, for example, resulting in impingement zones that occur at intervals along the length and/or the circumference of the inner passage. Applicant has discovered that introduction of such impingement features may increase the rate of heat transfer relative to the rate that would be attained by parallel flow through the outer passage. Moreover, Applicant has discovered that for a suitable level of heat transfer enhancement, a ratio of a velocity of an impinging flow to the superficial velocity may be greater than two, greaterthan five, or greaterthan ten. The velocity of the impinging flow may be approximated, in the case of nozzles or openings, as the volumetric flow divided by the total flow area defined by the nozzles or openings, through which the flow is directed.

[0100] Additionally, the heat transfer enhancement may be found to be more suitable at distances between the impingement-inducing feature (e.g., between nozzles or openings 1054) and the inner passage that are from about the diameter to about twelve times the diameter of the nozzles or openings 1054, from about the diameter to about ten times the diameter, or from about two times the diameter to about eight times the diameter. Examples of impingement features may include plate impingement and/or piccolo impingement. In certain embodiments at least one heat transfer enhancement in a first stage may be the same or different from at least one heat transfer enhancement in a second stage.

[0101] Referring now again to FIG. 2A, FIG. 2B, FIG. 3A, and FIG. 3B the outer annulus 1044 (see FIGS. 2A and 2B) of the thermal energy recovery assembly 1000 may include one or more structures to promote heat transfer from the reactor effluent or product gas P in the inner passage 1034 to the reaction feed F in the outer passage 1044 of the thermal energy recovery assembly 1000. For example, the thermal energy recovery assembly 1000 may include plate impingements 1050 in the outer annulus 1044 of the thermal energy recovery assembly 1000, for example, as shown in FIGS. 2A and 2B, and/or the thermal energy recovery assembly 1000 may include piccolo impingements 1060 (see also FIG. 3A) in the outer annulus 1044 (see also FIG. 3B) of the thermal energy recovery assembly 1000.

[0102] With particular reference to FIGS. 2A and 2B, the plate impingement 1050 may include the cooling medium (e.g., the reaction feed F) entering a first channel 1052 via a stage inlet 1043 that may be spaced apart from the inner passage 1034, for example, on an outside or outer circumference of the outer annulus 1044 of the thermal energy recovery assembly 1000. The cooling medium exits the first channel via one or more nozzles or openings 1054 in a wall 1055 into a second channel 1056 that is in contact with the inner passage 1034. The first channel 1052 may terminate in a downstream end 1058, for example, such that the cooling medium may be forced into the second channel 1056 to flow through the outer passage 1044 and exit through a stage outlet 1045 at a downstream end of the second channel 1056. The wall 1055 separates the first channel 1052 from the second channel 1056. The thermal energy recovery assembly 1000 may include one or more plate impingements 1050 disposed along the length thereof. Each plate impingement 1050 as shown in FIGS. 2A and 2B may be considered a plate impingement stage with the thermal energy recovery assembly 1000 including one or more plate impingement stages in series or parallel.

[0103] In some embodiments, one or more of the nozzles or openings 1054 may have a circular cross-section. In some such embodiments, the diameter of the one or more nozzles or openings 1054 may range from about 1 millimeter (mm) to about 15 mm, for example, from about 2 mm to about 10 mm, from about 3 mm to about 8 mm, or from about 4 mm to about 7 mm. In nozzles or openings 1054 not having a circular cross-section, the area of the cross-section of the nozzles or openings 1054 may substantially correspond to the area of nozzles or openings 1054 having a circular cross-section. In some embodiments, the nozzles or openings 1054 may be circumferentially aligned at different points along the longitudinal length of the wall 1055 or they may be circumferentially staggered along the longitudinal length of the wall, for example, in a helically extending manner. In some embodiments, wall 1055 may be spaced from the outer surface of the inner passage 1034 by a distance ranging, for example, when the nozzles or openings 1054 have a circular cross-section, from about a distance equal to the diameter of the nozzles or openings 1054 to about twelve times the diameter of the nozzles or openings 1054, or from about the diameter to about ten times the diameter, from about two times the diameter to about eight times the diameter.

[0104] In some embodiments, the nozzles or openings 1054 may be spaced around the circumference of the wall 1055. For example, at a given point along the longitudinal length of the wall 1055, the wall may include, for example, from one to fifteen nozzles or openings 1054, which may at least partially depend on the dimensions of the inner passage 1034, for example, with relatively more nozzles or openings 54 for relatively larger inner passages 1034. In some embodiments, the nozzles or openings 1054 may be circumferentially spaced around the inner passage 1034, for example, such that the spacing equals pi (i.e., 3.14159) multiplied by the sum of the diameter of the outer surface of the inner passage 1034 and two times the distance from the nozzles or openings 1054 to the outer surface of the inner passage 1034, all of which is divided by the number of nozzles or openings 1054 around the circumference. In some embodiments, the nozzles or openings 1054 may be spaced from one another substantially equally along the longitudinal length of the wall 1055 and/or substantially equally circumferentially around the wall 1055.

[0105] With reference to FIGS. 3A and 3B, the piccolo impingement 1060 may include the cooling medium (e.g., the feed) entering one or more piccolo or outer passages 1062 and a chamber 1066 defined about the inner passage 1034. In some embodiments, the chamber 1066 may generally define an outer passage, such as, for example, the outer passage or annulus 1044 shown in FIGS. 2A and 2B. The outer passages 1062 may include a stage inlet 1043 and may include one or more nozzles or openings 1064 configured to allow the cooling medium to flow from the outer passages 1062 into the chamber 1066, for example, such that the cooling medium is in contact with the inner passage 1034. In some embodiments, one or more of the nozzles or openings 1064 may be directed at an outer surface of the inner passage 1034, for example, as shown in FIG. 3B. The chamber 1066 may be defined between a first or upstream divider 1065 and second or downstream divider 1067. The upstream divider 1065 may include openings that allow the cooling medium to enter the outer passages 1062. The downstream divider 1067 may terminate a downstream end of each of the outer passages 1062 and may include outlets defined therein that allow the cooling medium to exit the chamber 1066 and flow into another set of outer passages 1062 or exit the thermal energy recovery assembly 1000. The thermal energy recovery assembly 1000 may include one or more piccolo impingements 1060 disposed along the length thereof. Each piccolo impingement 1060, as shown in FIGS. 3A and 3B, may be considered a piccolo impingement stage with the thermal energy recovery assembly 1000 including one or more piccolo impingements in series or parallel with one another.

[0106] In some embodiments, one or more of the nozzles or openings 1064 may have a circular cross-section. In some such embodiments, the diameter of the one or more nozzles or openings 1064 may range from about 1 millimeter (mm) to about 15 mm, for example, from about 2 mm to about 10 mm, from about 3 mm to about 8 mm, or from about 4 mm to about 7 mm. In nozzles or openings 1064 not having a circular cross-section, the area of the cross-section of the nozzles or openings 1064 may substantially correspond to the area of nozzles or openings 1064 having a circular cross-section. In some embodiments, the nozzles or openings 1064 may be circumferentially aligned relative to the respective outer passages 1062, such that fluid passing through each of the nozzles or openings 1064 is directed at the outer surface of the inner passage 1034, for example, at an angle of about ninety degrees relative to the outer surface of the inner passage 1034. In some embodiments, one or more of the nozzles or openings 1064 may be circumferentially oriented relative to its respective outer passage 1062, such that fluid passing through the nozzle or opening 1064 is at a non-perpendicular angle relative to the outer surface of the inner passage 1034, ranging, for example, from about ten degrees to about eighty degrees, twenty degrees to about eighty degrees, thirty degrees to about eighty degrees, or about forty-five degrees to about eighty degrees. In some embodiments, the nozzles or openings 1064 may be located at different points and circumferentially aligned along the length (e.g., in a direction along the longitudinal axis) of the outer passage 1062. In some embodiments, nozzles or openings 1064 may be spaced from the outer surface of the inner passage 1034 by a distance ranging, for example, when the nozzles or openings 1064 have a circular cross-section, from about a distance equal to the diameter to the nozzle or opening 1064 to about twelve times the diameter of the nozzle or opening 1064, or from about the diameter to about ten times the diameter, from about two times the diameter to about eight times the diameter.

[0107] In some embodiments, each of the outer passages 1062 may include a single nozzle or opening 1064 at each of a plurality of locations along the length of the outer passages 1062. In some embodiments, each of the outer passages 1062 may include a number of nozzles or openings 1064 ranging from one to fifteen nozzles or openings 1064, from one to ten nozzles or openings 1064, from one to five nozzles or openings 1064 (e.g., four nozzles or openings 1064) or from five to ten nozzles or openings 1064. In some embodiments, the distance between nozzles or openings 1064, for example, on a respective outer passage 1062 may be defined, such that the distance between adjacent nozzles or openings 64 divided by diameter of the nozzle or opening 1064 is greater than or equal to one and less than or equal to twenty. The number of outer passages 1062 in a stage may be between one and twelve, or between two and six.

[0108] The thermal energy recovery assembly 1000 in FIG. 2A and 2B may have a modular design with a plurality of stages along a length thereof. For example, the thermal energy recovery assembly 1000 may include one or more plate impingement stages 1050 and one or more piccolo impingement stages 1060. In some embodiments, the thermal energy recovery assembly 1030 may include only plate impingement stages 1050 or may include only piccolo impingement stages 1060. In particular embodiments, the thermal energy recovery assembly 1000 may include plate impingement stages 1050, piccolo impingement stages 1060, and turbulence-promoting (TP) features or turbulence-promoting stages.

[0109] The thermal energy recovery assembly 1000 in FIG. 2A and 2B may be used in conjunction with a conventional gas to liquid steam-raising TLE. For example, a conventional TLE may be used to perform the initial quenching of the reactor effluent and then be followed by the thermal energy recovery assembly 1000, as long as the reactor effluent enters the thermal energy recovery assembly 1000 at a temperature of at least 550 °C, at least 575 °C, at least 600 °C, at least 610 °C, at least 620 °C, at least 630 °C, at least 640 °C, at least 650 °C, at least 700 °C, at least 750 °C, or at least 800 °C, or at least 850 °C. Alternatively, the thermal energy recovery assembly 1000 may be followed by a conventional TLE, for example, if the thermal energy recovery assembly 1000 preheats the feed to at least 350 °C, at least 375 °C, at least 400 °C, at least 425 °C, at least 450 °C, at least 475 °C, at least 500 °C, at least 525 °C, at least 550 °C, at least 575 °C, at least 600 °C, at least 625 °C, or at least 650 °C. For example, the fired cracking furnace assembly may include a conventional TLE before or after the thermal energy recovery assembly 1000. For example, the reactor effluent line and/or the quenched effluent line may include a conventional TLE. In some embodiments, the conventional gas-to-liquid steam-raising TLE may be part of the same assembly as the thermal energy recovery assembly 1000. In some embodiments, the thermal energy recovery assembly 1000 according to some embodiments may be combined with superheating a steam stream.

[0110] The characteristics of the stages of the thermal energy recovery assembly 1000 in FIG. 2A and 2B may be tuned depending, for example, on the position of the stage within the thermal energy recovery assembly 1000. For example, when the thermal energy recovery assembly 1000 includes plate impingement stages 1050, the channels 1052 and/or 1056, the nozzles or openings 1054, and/or the length of the plate impingement stages 1050 may be sized and dimensioned to optimize heat transfer for conditions at that position along the thermal energy recovery assembly 1000. As such, the first channel 1056 of a stage 1050 at a first position along the thermal energy recovery assembly 1030 may have a radial height greater than a radial height of a first channel 1056 of a stage 1050 at a second position along the thermal energy recovery assembly 1000. Similarly, the nozzles or openings 1054 of a stage 1050 at the first position may have a diameter less than a diameter of nozzles or openings 1054 of a stage 1050 at a second position. In some embodiments, the radial height may remain substantially equal between one or more stages. In some embodiments, when the thermal energy recovery assembly 1000 includes piccolo impingement stages 1060, the diameter of the outer passages 1062, the size and/or number of the nozzles 1064, and/or the length of the piccolo impingement stages 1060 may be sized and dimensioned to optimize heat transfer for conditions at that position along the thermal energy recovery assembly 1030. In some embodiments, the number of nozzles or openings 1054 from stage to stage may be higher, lower, or the same. In some embodiments, the number of rows of nozzles or openings 1054 may vary from stage to stage. The conditions along the thermal energy recovery assembly 1030 may include the temperature of the reactor effluent, the temperature of the feed, the inlet and/or outlet pressure of the reactor effluent, the inlet and/or outlet pressure of the feed, the pressure drop of the reactor effluent along the length of the assembly pressure, the pressure drop of the feed along the length of the thermal energy recovery assembly 1000, the temperature difference between the feed and the reactor effluent, the velocity of the reactor effluent, and/or the velocity of the feed.

[0111] As noted above, the thermal energy recovery assembly 1000 may include stages that are parallel with one another. The thermal energy recovery assembly 1000 may activate or deactivate one or more of these parallel stages based on a temperature of hot reactor effluent entering the thermal energy recovery assembly 1000 or a temperature of quenched reactor effluent exiting the thermal energy recovery assembly 1000. When a stage is activated, hot reactor effluent is flowing through the stage and when a stage is deactivated, hot reactor effluent is prevented from flowing through the stage. For example, when the quenched reactor effluent exiting the thermal energy recovery assembly 1000 is above a desired temperature, the thermal energy recovery assembly 1000 may activate another stage or stages and when the quenched reactor effluent or product gas P exiting the thermal energy recovery assembly 1000 may deactivate a stage or stages.

[0112] As noted above, the thermal energy recovery assembly 1000 may include stages that are in series with one another. The thermal energy recovery assembly 1000 may activate or deactivate one or more of these stages based, for example, on the temperature of hot reactor effluent entering the thermal energy recovery assembly 1000, the temperature of quenched reactor effluent exiting the thermal energy recovery assembly 1000, the temperature of feed entering thermal energy recovery assembly 1000, and/or the temperature of feed exiting thermal energy recovery assembly 1000. In some embodiments, when a stage is activated, feed may flow through the activated stage, and when a stage is deactivated, feed is prevented from flowing through the deactivated stage. For example, when the quenched reactor effluent exiting the thermal energy recovery assembly 1000 is above a desired temperature, the thermal energy recovery assembly 1000 may activate one or more additional stages so that the temperature of the quenched reactor effluent exiting the thermal energy recovery assembly 1000 decreases toward the desired temperature, and/or when the quenched reactor effluent exiting the thermal energy recovery assembly 1000 is below a desired temperature, the thermal energy recovery assembly 1000 may deactivate one or more stages so that the temperature of the quenched reactor effluent exiting the thermal energy recovery assembly 1000 increases toward the desired temperature. In some embodiments, the thermal energy recovery assembly 1000 may include one or more controllers configured to control operation of one or more of the stages, for example, as will be understood by those skilled in the art. For example, the thermal energy recovery assembly 1000 may include a plurality of temperature sensors, pressure sensors, flow rate sensors, etc., in communication with the controller, and the controller may use control logic in the form of computer software and/or hardware programs to make control decisions associated with controlling operation of the thermal energy recovery assembly 1000, for example, including the one or more stages. In some embodiments, the thermal energy recovery assembly 1000 may include valves associated with the lines and/or conduits, and the controller may communicate control signals based at least in part on the control decisions to actuators associated with the valves to control the flow of fluid (e.g., gases and/or liquids) and/or heat, and the actuators may be operated according to the communicated control signals to operate the parts of the thermal energy recovery assembly 1000. In some examples, the controller may be supplemented or replaced by human operators at least partially manually controlling the thermal energy recovery assembly 1000 to meet desired performance parameters based at least in part on efficiency considerations.

[0113] In some embodiments, the thermal energy recovery assembly 1000 through FIG 2A to 3B may be configured to quench the hot reactor effluent within a residence time and/or with a pressure drop consistent with other quenching devices of a gas-fired cracking furnace. In some embodiments, the thermal energy recovery assembly 1000 may be tuned or optimized to be substantially equivalent to, or improved relative to, other types of quenching devices. For example, the thermal energy recovery assembly 1000 may be configured such that a residence time, as measured by the time within the thermal energy recovery assembly 1000, is less than 100 milliseconds (ms), for example, less than 90 ms, or less than 85 ms (e.g., less than 83 ms); that a pressure drop of the reactor effluent is less than 0.35 bar, for example, less than 0.30 bar, less than 0.25 bar, or less than 0.20 bar (e.g., less than 0.15 bar); and/or that a cooling rate is greater than 2.5 degrees Kelvin (K)/ms, for example, greater than 3.5 K/ms, greater than 4.0 K/ms, greater than 4.5 K/ms, at least 5 degrees K/ms, or at least 5.5 degrees K/ms, for example, where the cooling rate may be defined as the inlet temperature of the hot reactor effluent (in degrees K) minus 923 K, divided by the residence time required for cooling from the temperature of the hot reactor effluent to 923 K, unless the inlet temperature of the hot reactor effluent (in degrees K) is less than 923 K or the temperature of the cooled reactor effluent is greater than 923K, in which case the cooling rate may be defined as the inlet temperature of the hot reactor effluent (in degrees K) minus the temperature of the cooled reactor effluent when it leaves the thermal energy recovery assembly, divided by the residence time of the effluent in the assembly. Thermal energy recovery assembly 1000 may be configured to achieve, in addition to the effluent-side pressure drop and cooling rate performance, a pressure drop of the feed from 2 to 15 bar, for example, from 2.5 to 10 bar, from 3 to 8 bar, from 3 to 10 bar, or from 4 to 9 bar (e.g., from 5 to 8 bar), for example, to manage the amount of pressurization required before the reaction feed F enters the thermal energy recovery assembly 1000 while promoting a sufficiently high rate of heat transfer from the inner passage to the feed. Upper and lower temperature levels have already been mentioned above.

[0114] In some embodiments, the thermal energy recovery assembly 1000 may be configured and/or controlled to quench the hot reactor effluent or product gas P and to preheat the reaction feed F to a reactor feed temperature. For example, the thermal energy recovery assembly 1000 may be configured with one or more stages to transfer heat from the hot reactor effluent to the reaction feed, which may not be preheated, or at least not preheated sufficiently to supply to a cracking furnace for cracking. In some embodiments, the stages may have a passage-in-passage design with the hot reactor effluent or product gas P flowing through an inner passage and the reaction feed F flowing through an outer passage. The outer passage may include stages having one or more heat transfer enhancements, such as, for example, plate impingement, piccolo impingement, one or more turbulence promoting features associated with the outer passage and/or the inner passage, and/or increased surface area associated with the outer passage and/or the inner passage. For example, the inner passage may include one or more heat transfer enhancements configured to promote heat transfer from the hot reactor effluent or product gas P. Configuring the one or more stages and inner passage may include selecting stages to achieve desired properties of the hot reactor effluent or product gas P while transferring heat to the cold reaction feed F. For example, stages may be selected to improve or maximize a cooling rate of the hot reactor effluent, to improve or minimize a pressure drop of the hot reactor effluent, to improve or minimize a residence time of the hot reactor effluent, and/or to improve or minimize a pressure drop of the reaction feed.

[0115] In some embodiments, the thermal energy recovery assembly may include a plurality of inner passages parallel with one another, with each inner passage disposed within an outer passage and each outer passage having one or more heat transfer enhancements to enhance heat transfer from the inner passage to an outer passage defined within the outer passage. In some embodiments, the thermal energy recovery assembly may include a plurality of inner passages parallel with one another, with each inner passage disposed within an outer passage, and with the outer passage and optionally the inner passage having one or more heat transfer enhancements to enhance heat transfer from the inner passage to an outer passage defined within the outer passage.

[0116] FIG. 4A is a schematic section view of an example inner passage 1034a including example rounded projections 1070a on an interior surface 1072a of the inner passage 1034a, according to embodiments of the disclosure. As shown in FIG. 4A, in some embodiments, the interior surface 1072a of the inner passages 1034a may include turbulence-promoting structures and/or structures to increase the surface area of the interior surface 1072a. For example, as shown in FIG. 4A, the interior surface 1072a of the inner passage 1034a may include one or more rounded projections 1070a. In some embodiments, the one or more rounded projections 1070a may extend toward the center of the inner passage 1034a and/or may extend longitudinally, partially, intermittently, or fully, along the length of the inner passage 1034a. In some embodiments, the rounded projections 1070a may be the same or differ from one another. In some embodiments, the one or more rounded projections 1070a may extend helically along the longitudinal length of the inner passage 1034a, for example, to promote swirling of the flow through the inner passage 1034a. In some embodiments, projections on the interior surface of inner passages 1034a may have a non-rounded configuration.

[0117] For example, FIG. 4B is a schematic section view of another example inner passage 1034b including example rectangular projections 1070b on an interior surface 1072b of the inner passage 1034b, according to embodiments of the disclosure. In some embodiments, the interior surface of the inner passages 1034 may include a combination of rounded projections and rectangular projections.

[0118] Other configurations of projections are contemplated. In some embodiments, the inner passage 1034 may include turbulence promoting structures and/or structures to increase the surface area of an outer surface of the inner passage 1034. For example, turbulence promoting structures and/or structures to increase the surface area of the outer surface of the inner passage 1034 may include projections at least similar to the above-noted projections on the interior surface of the inner passage 1034. In some embodiments, structures to increase the surface area of the outer surface of the inner passage 1034 may be configured to enhance the effectiveness of the turbulence-promoting structures and/or impingement features. In some embodiments, the inner surface of the outer passage 1040 may include surface area enhancements, for example, such as those described above.

[0119] FIG. 5 is a block diagram of an example method 2000 to heat a reaction feed including, for example, one or more of ethane, propane, butane, condensate, light naphtha, heavy naphtha, gas oil, pyrolysis oil, materials derived from processing refinery streams, Fischer-Tropsch products, plastic waste, and/or biofeedstocks. The reaction feed may additionally include steam. The reaction feed may be preheated and thereafter cracked in a highly efficient and low emission gas-fired cracking furnace, which may output cracked hydrocarbons including olefins.

[0120] The example method 200, according to some embodiments, is illustrated in FIG. 5 as a collection of blocks in a logical flow graph, which represent a sequence of operations. The order in which the operations are described is not intended to be construed as a limitation, and any number of the described blocks may be combined in any order and/or in parallel to implement the method. Moreover, the operations described in one or more of the blocks may be optional and/or omitted from the example method 2000, such as, for example, the operations described by blocks 2012 and/or 2014, although one or more of the operations described by other blocks may also, or alternatively, be omitted from the example method 2000.

[0121] The example method 2000, at 2002, may include supplying a hydrocarbon or reaction feed to an outer passage of a thermal energy recovery assembly. For example, the thermal energy recovery system may include any thermal energy recovery systems described herein. As noted above, the reaction feed may include, for example, one or more of ethane, propane, butane, condensate, light naphtha, heavy naphtha, gas oil, pyrolysis oil, and/or materials derived from processing refinery streams, Fischer-Tropsch products, plastic waste, or biofeedstocks, or any other hydrocarbons that may be converted to olefins in a cracking process, and may additionally include steam. The reaction feed may, in some embodiments, include, or be, a reaction feed supplied by a source of reaction feed.

[0122] At 2004, the example method 2000 further may include heating the reaction feed in the outer passage of the thermal energy recovery assembly to output a preheated reaction feed. For example, as explained herein, the reaction feed may be preheated via heat transfer in the thermal energy recovery system with the thermal energy being at least partially supplied by hot reactor effluent of the cracking process.

[0123] The example method 2000, at 2006 also may include supplying the preheated reaction feed to a highly efficient and low emission gas-fired cracking furnace including a reaction zone to heat the preheated reaction feed, for example, as previously described herein.

[0124] At 2008, the example method 500 further may include cracking the preheated reaction feed in the reaction zone to output hot reactor effluent including cracked hydrocarbons and olefins, for example, as described previously herein.

[0125] The example method 2000, at 2010, also may include supplying the hot reactor effluent to an inner passage of the thermal energy recovery assembly, for example, as previously described herein. For example, in some embodiments, supplying the hot reactor effluent to the inner passage of the thermal energy recovery assembly may include supplying the hot reactor effluent to the inner passage of the thermal energy recovery assembly at a temperature of at least 350° Celsius, at least 375° Celsius, at least 400° Celsius, at least 425° Celsius, at least 450° Celsius, at least 475° Celsius, at least 500° Celsius, at least 525° Celsius, at least 550° Celsius, at least 575° Celsius, at least 600° Celsius, at least 625° Celsius, at least 650° Celsius, at least 700 °C, at least 750 °C, at least 800 °C, or at least 850 °C.

[0126] At 512, the example method 2000 further may include supplying additional feed to the outer passage of the thermal energy recovery assembly. The additional feed may, in some embodiments, be a continuation of the supply of reaction feed at 2002 from the reaction feed source, a different reaction feed, water, or steam. The additional feed may be supplied to a stage different from the stage to which the reaction feed is supplied. The additional feed may mix with the reaction feed, the mixed feed exiting the thermal energy recovery assembly at a common outlet. The additional feed may traverse different stages than does the reaction feed, and exit through a different outlet.

[0127] The example method 2000, at 2014, also may include heating the additional feed by transferring heat from the hot reactor effluent to the additional reaction feed via the thermal energy recovery assembly, for example, as described previously herein. Heating the additional feed in the outer passage of the thermal energy recovery assembly to output a preheated feed may include heating the feed to a temperature of at least 350° Celsius, at least 375° Celsius, at least 400° Celsius, at least 425° Celsius, at least 450° Celsius, at least 475° Celsius, at least 500° Celsius, at least 525° Celsius, at least 550° Celsius, at least 575° Celsius, at least 600° Celsius, at least 625° Celsius, or at least 650° Celsius. In some embodiments, supplying the hot reactor effluent to the inner passage of the thermal energy recovery assembly may include quenching the hot reactor effluent via heat transfer to the additional reaction feed, for example, as described herein. In some embodiments, heating the feed in the outer passage of the thermal energy recovery assembly may include preheating the feed via heat transfer to the feed from the hot reactor effluent. In some embodiments, the example method 2000 may further include enhancing the heat transfer to the additional feed by providing heat transfer enhancements on one or more of the outer passage or the inner passage. The heat transfer enhancements may include one or more of plate impingement, piccolo impingement, turbulence promotion, or increased surface area, for example, as previously described herein.

[0128] At 2016, the example method 2000 further may include the utilization of flue gas heat in the convection zone for oxidant preheating in one or multiple steps. Furthermore, indirect use of heat in the form of steam or heated boiler feed water from hot reactor effluent quench may be used in addition for oxidant preheating

[0129] At 2018, the example method 2000 further may include the combustion of preheated oxidant with hydrogen or a hydrogen rich fuel gas in a fired cracking furnace.

[0130] With reference to FIG. 6 and to FIG.7 for a one-stage application of the passage-in-passage gas-gas exchanger within the energy recovery assembly the reactor effluent or product gas may be either in countercurrent (FIG. 6) or cocurrent flow-direction (FIG. 7) to the reaction feed. A product gas inlet is indicated 1 while an outlet thereof is indicated 2. A reaction feed inlet is indicated 3 while an outlet thereof is indicated 4. The hot reactor effluent or product gas is supplied to the inner passage and the reaction feed to the outer passage disposed about the inner passage to enclose an annulus, as described before. The outer passage may include at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage through impingement, turbulence promotion, high shear inducing geometry, or increased surface area.

[0131] With reference to FIG. 8 and FIG. 9 for a two-staged application of the passage-in-passage gas-gas exchanger within the energy recovery assembly the flow-direction of the reactor effluent or product gas may be cocurrent with the feed in a first stage and countercurrent to the feed in a second stage. Again, a product gas inlet is indicated 1 while an outlet thereof is indicated 2. A reaction feed inlet is indicated 3 while an outlet thereof is indicated 4. The hot reactor effluent or product gas is supplied to the inner passage and the reaction feed to the outer passage disposed about the inner passage to enclose an outer passage. The outer passage may include at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage through impingement, turbulence promotion, high shear inducing geometry, or increased surface area. The heat transfer enhancement method applied and the detailed layout may be identical for both stages or may be different.

[0132] In some embodiments of the two-staged application the cold reaction feed may enter the passage-in-passage gas-gas exchanger at the cocurrent stage, in which the first preheating takes places and may be further heated in the countercurrent stage (FIG 8). The hot reactor effluent or product gas is supplied to the inner passage and the reaction feed to the outer passage disposed about the inner passage to enclose an outer passage. The outer passage may include at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage through impingement, turbulence promotion, high shear inducing geometry, or increased surface area. The heat transfer enhancement method applied and the detailed layout may be identical for both stages or may be different.

[0133] In some embodiments of the two-staged application the cold reaction feed may enter the passage-in-passage gas-gas exchanger at the countercurrent stage, in which the first preheating takes places and may be further heated in the cocurrent stage (FIG. 9). The hot reactor effluent or product gas is supplied to the inner passage and the reaction feed to the outer passage disposed about the inner passage to enclose an outer passage. The outer passage may include at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage through impingement, turbulence promotion, high shear inducing geometry, or increased surface area. The heat transfer enhancement method applied and the detailed layout may be identical for both stages or may be different.

[0134] In some embodiments, the countercurrent stage constitutes a separate thermal energy recovery assembly and may be built as a conventional passage-in-passage or shell-and-passage type heat exchanger.

[0135] With reference to FIG. 10 for a two-staged application of the passage-in-passage gas-gas exchanger within the energy recovery assembly the flow-direction of the reactor effluent or product gas may be cocurrent with the reaction feed in a first stage and cocurrent with the reaction feed in a second stage. Again, a product gas inlet is indicated 1 while an outlet thereof is indicated 2. A reaction feed inlet is indicated 3 while an outlet thereof is indicated 4. The hot reactor effluent or product gas is supplied to the inner passage and the reaction feed to the outer passage disposed about the inner passage to enclose an outer passage. The outer passage may include at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage through impingement, turbulence promotion, high shear inducing geometry, or increased surface area. The heat transfer enhancement method applied and the detailed layout may be identical for both stages or may be different.

[0136] In some embodiments of the two-staged application the cold reaction feed may enter the passage-in-passage gas-gas exchanger at the second cocurrent stage from a reactor effluent or product gas flow perspective, in which the first preheating takes places and may be further heated in a first cocurrent stage (FIG. 10). The hot reactor effluent or product gas is supplied to the inner passage and the reaction feed to the outer passage disposed about the inner passage to enclose an outer passage. The outer passage may, as repeatedly indicated, include at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage through impingement, turbulence promotion, high shear inducing geometry, or increased surface area. The heat transfer enhancement method applied and the detailed layout may be identical for both stages or may be different.

EXAMPLES

Example 1

[0137] The heat transfer performance of several thermal energy recovery assemblies that include heat transfer enhancements according to embodiments of this disclosure was compared to the performance of a conventional passage-in-passage gas-gas heat exchanger. The conventional heat exchanger was designed for a feed-side pressure drop of 1.76 bar, and did not include enhancements in either an inner passage or an outer passage. The thermal energy recovery assemblies according to embodiments of the disclosure were configured as follows:

(1) a passage-in-passage thermal energy recovery assembly without heat transfer enhancement in an inner passage and with high-shear geometry in an outer passage, (2) a thermal energy recovery assembly including fins in the inner passage and turbulence-promoting features in the outer passage, (3) a thermal energy recovery assembly including fins in the inner passage and plate impingement in the outer passage, (4) a thermal energy recovery assembly including fins in the inner passage and piccolo impingement in the outer passage, (5) a thermal energy recovery assembly including a plain passage (no internal fins) and turbulence promoting features in the outer passage, (6) a thermal energy recovery assembly including a plain passage and plate impingement in the outer passage, and (7) a thermal energy recovery assembly including a plain passage and piccolo impingement in the outer passage.

[0138] For the purpose of the comparison, boundary conditions for the conventional heat exchanger ("Comp.") and each of the seven example thermal energy recovery assemblies according to embodiments of the disclosure (1 through 7) were established as follows: hot effluent resulting from steam cracking of ethane was passed through an inner passage, and cold feed including ethane and steam was passed through an outer passage. The hot effluent mass flow rate was 351.6 kilograms/hour, and the outer diameter of the inner passage was 60.3 mm, with a passage wall thickness of 3.6 mm. The hot effluent and the cold feed provided in a countercurrent flow arrangement as explained above, with the following inlet and outlet temperatures (T_{in}, T_{out}) for the hot effluent and the cold feed: $T_{in, hot}$ equals 827 °C; $T_{out, hot}$ equals 486 °C; $T_{in, cold}$ equals 236 °C; and $T_{out, cold}$ equals 650 °C according to this embodiment.

[0139] Software tools designed for calculation of heat transfer were used to assess the performance of the conventional heat exchanger ("Comp.") and the seven examples according to embodiments of the disclosure. Table A below shows the comparative performance in terms of various metrics explained below. For each metric, the value for each of the thermal energy recovery assemblies according to embodiments of the disclosure (1 through 7) is listed relative to the corresponding value for the conventional heat exchanger. The example metrics provided for comparison are the effluent cooling rate, the heating surface area, the pressure drops on the feed and effluent sides of the corresponding device, and the effluent residence time.

TABLE A

Device	Comp.	1	2	3	4	5	6	7
Outer passage enhancement	None	High-shear	TP	Plate	Piccolo	TP	Plate	Piccolo
Inner passage enhancement	None	None	Finned	Finned	Finned	None	None	None
Relative cooling rate	1	1.08	1.47	1.51	1.58	1.14	1.16	1.22
Relative heating surface	1	0.91	0.74	0.71	0.70	0.87	0.85	0.80
Relative feed pressure drop	1	2.24	3.40	3.92	3.48	3.77	3.66	3.47
Relative effluent pressure drop	1	0.93	1.23	1.18	1.26	0.90	0.88	0.84
Relative residence time	1	0.91	0.69	0.68	0.65	0.87	0.85	0.80

[0140] As shown in Table A, thermal energy recovery assemblies according to embodiments of the disclosure may provide improved performance, for example, in terms of cooling rate, residence time, effluent pressure drop, and/or required cooling surface area as compared to a heat exchanger without such heat transfer enhancement features. As will be clear from this disclosure, higher values of the cooling rate and lower values of the required surface area, the effluent pressure drop, and the effluent residence time may be generally favorable in terms of process performance and/or equipment cost.

Examples 2(a) and 2(b)

[0141] For liquid feedstock and gaseous feedstocks, energy balancing through process simulation software and proof of technical feasibility through furnace and equipment design tools result in the following exemplary figures of example 2a and 2b, illustrating the lever for reduction of fired duty and greenhouse gas emissions in the embodiments under consideration here.

[0142] Example 2(a) is a comparative performance analysis of processing 48 tons per hour of naphtha in a conventional state-of-the-art cracking furnace without oxidant preheat versus a high efficiency, low-emission fired steam cracking furnace combined with a thermal energy recovery assembly according to embodiments of the present disclosure shown in FIGS. 1A and 1C.

[0143] The following basic parameters were chosen for the comparison:

- Naphtha feedstock rate: 48 tons per hour, 70 °C
- Diluent Steam: 24 tons per hour, 190 °C
- Propylene to Ethylene Ratio 0.45 (Cracking Severity)
- Fuel Gas Composition: 78 Vol.% Hydrogen, 12% Methane
- Oxidant Ambient Air at 20 °C
- Steam conditions: 115 bar, 505 °C

[0144] The thermal energy recovery unit 12 and 13 in FIG. 1A and FIG. 1C is configured as a two stage cocurrent/countercurrent exchanger (B) (according FIG. 9), which enables a heat transfer of the available hot reactor effluent heat to the preheated feedstock from 30% (2a-1) to 50% (2a-2) up to 70% (2a-3). Combustion air is externally preheated to 300

°C against VHP steam and further heated in the convection zone of the fired furnace. That enables air preheat temperatures of 430 °C (2a-1), 600 °C (2a-2) or even up to 700 °C (2a-3). The reduction in fired duty at the furnace burners sums up to 20% in 2a-1, to 40% in 2a-2 to and up to 45% in example 2a-3. The net steam export from the furnace and heat integration unit is thereby reduced by more than 60% in 2a-1, almost 80% in 2a-2 and almost 90 % in 2a-3. Reference is made to table B.

TABLE B

	Conventional Furnace	2a-1	2a-2	2a-3
Embodiment according to	-	FIG A	FIG A	FIG C
Air Preheat Temperature [°C]	20	430	620	700
Normalized Fired Duty Furnace in %	100	80	60	55
Proportional Duty Feed/Effluent HEX [% of available cracked gas heat]	-	30	50	70
Net Steam Export [t/h] @ 115 bar, 505 °C	60	22	13	7

[0145] Example 2(b) is a comparative performance analysis of processing 51 tons per hour of ethane in a conventional state-of-the-art cracking furnace without oxidant preheat versus a high efficiency, low-emission fired steam cracking furnace combined with a thermal energy recovery assembly according to embodiment in FIG 1D.

[0146] The following basic parameters were chosen for the comparison:

- Ethane feedstock rate: 51 tons per hour, 70 °C
- Diluent Steam: 15.3 tons per hour, 190 °C
- Ethane Conversion: 60%
- Fuel Gas Composition: 100 Vol.% Hydrogen
- Oxidant: Ambient Air at 20 °C
- Steam conditions: variable (115 bar, 505 °C and 42 bar, 450 °C)

[0147] The thermal energy recovery unit 12 and 13 in FIG. 1D is configured as a two-stage cocurrent/countercurrent exchanger (B) (according FIG. 9), which enables a heat transfer of the available hot reactor effluent heat to the preheated feedstock of from 30% (2b-1) to 50% (2b-2) . Combustion air is externally preheated to approx. 250 °C against preheated boiler feed water. The air is further heated in the convection zone of the fired furnace in an air preheater I and II. Air preheat temperatures of 600 °C (2b-1) or even up to 780 °C (2b-2) can be reached by such a design. The reduction in fired duty at the furnace burners sums up to approx. 45% in example 2b-1 and 2b-2. The net steam export from the furnace and heat integration unit is thereby reduced by more than 60% in 2b-1 and 2b-2. Reference is made to Table C below.

TABLE C

	Conventional Furnace	2b-1	2b-2
Embodiment according to	-	FIG D	FIG D
Air Preheat Temperature [°C]	20	700	780
Normalized Fired Duty Furnace in %	100	56	54
Proportional Duty Feed/Effluent HEX [% of available cracked gas heat]	-	53	52
Net Steam Export [t/h]	75		
(115 bar, 505 °C)	27		
(115 bar, 505 °C)	26		
(42 bar / 450 °C)			

Examples 3(a) through 3(c)

[0148] In examples 3(a) through 3(c) for an ethane application case a feed-effluent heat exchanger is used for the primary cooling and steam generation is used for the secondary cooling. The examples 3(a) to 3(c) differ with respect to the configuration of the feed-effluent heat exchanger. Generally, example 3(a) may essentially correspond to FIG. 6, example 3(b) may essentially correspond to FIG. 8 and example 3(c) may essentially correspond to FIG. 9. In example 3(a) the feed-effluent heat exchanger comprises one stage and is countercurrent. In example 3(b) and 3(c) the feed-effluent heat exchanger comprises two stages with a first cocurrent and a second countercurrent stage. In example 3(b) the cold feed is routed to the cocurrent stage first and then routed to the countercurrent stage. In example 3(c) the cold feed is routed to the countercurrent stage first and then routed to the cocurrent stage. In all three examples 3(a) through 3(c) the reactor effluent flow and the feed flow is identical. In all three examples 3(a) to (c) the feed is heated from 230 °C to 580 °C and the reactor effluent cooled from 849 °C to 561 °C. A summary of the results of examples 3(a) through 3(c) is given in Table D below, in which a passage according to a corresponding embodiment is referred to as a "tube". Except for the passage metal temperatures for each metric, the value for each of the examples 3(a) to 3(c) is listed relative to the corresponding value of example 3(a). The example metrics provided for comparison are the heat transferred, the passage inside pressure drop, the effluent residence time, the cooling rate and the required heating surface area.

[0149] The highest passage surface temperatures at the inner passage are expected for example 3(a), while the lowest inner passage surface temperatures are expected for example 3(b). As a consequence, the risk to enter regimes, where coking due to pre-cracking at the passage outside surface and enhanced chemical coking at the passage inside surface is highest for a configuration represented by example 3(a). The resulting inner passage surface temperatures of example 3(c) are in between example 3(a) and 3(b), but closer to 3(b). At the cold end of the assembly the lowest passage inside temperatures are expected for example 3(a) and 3(c), while example 3(b) exhibits higher passage inside temperatures. For the ethane application examples shown herein the risk of significant condensation coking is low.

[0150] With respect to the passage inside effluent pressure drop, which has impact on the cracking selectivity, it is lowest for example 3(a), followed by example 3(c) and is significantly higher for example 3(b). The high effluent pressure drop in example 3(b) results from the significantly higher passage length compared to example 3(a) and 3(c).

[0151] With respect to residence time and cooling rate, referred to a cooling of the effluent until a temperature of 650 °C, advantageous values may be obtained with the configuration of example 3(b), which may be due to the highest temperature differences between effluent and feed at the effluent inlet.

[0152] However, taking into account the required and comparable high heat transfer surface of example 3(b) and the high passage metal temperatures seen for example 3(a) the configuration as defined for example 3(c) may be considered advantageous if heat transfer surface is limited.

[0153] Generally, the skilled person will select from the configurations of examples 3(a) through 3(c) depending depending on requirements given by specific technical and economical boundary conditions.

Table D

Example		**3(a)**	**3(b)**	3(c)
Heat transferred	[%]	100	100	100
Tube inside pressure drop	[%]	100	176	108
Tube metal temperatures				
max. inside tube	[°C]	668	600	615
max. outside tube	[°C]	644	595	605
min. inside tube	[°C]	331	451	333
residence time	[%]	100	87	112
cooling rate	[%]	100	115	89
Heat transfer surface	[%]	100	193	108

Example 4(a) through 4(c)

[0154] In examples 4(a) through 4(c) for a naphtha application case, a feed-effluent heat exchanger was used for the primary cooling, and steam generation was used for the secondary cooling. The examples 4(a) to 4(c) differ with respect to the configuration of the feed-effluent heat exchanger. In example 4(a), the feed-effluent heat exchanger comprised one stage and was in countercurrent configuration. In example 4(b) and 4(c) the feed-effluent heat exchanger comprises two stages with a first cocurrent and a second countercurrent stage. In example 4(b) the cold feed is routed to the cocurrent stage first and then routed to the countercurrent stage. In example 4(c) the cold feed is routed to the countercurrent stage first and then routed to the cocurrent stage. In all three examples 4(a) through 4(c) the reactor effluent flow and the feed flow is identical. In all three examples 4(a) to (c) the feed is heated from 223 °C to 594 °C and the reactor effluent cooled from 862 °C to 539 °C. A summary of the results of examples 4(a) through 4(c) is given in Table E below. Except for the passage metal temperatures for each metric, the value for each of the examples 4(a) to 4(c) is listed relative to the corresponding value of example 4(a). The example metrics provided for comparison are the heat transferred, the passage inside pressure drop, the effluent residence time, the cooling rate and the required heating surface area.

[0155] The highest passage surface temperatures at the inner passage are expected for example 4(a), while the lowest inside passage surface temperatures are expected for example 4(b). As a consequence, the risk to enter regimes, where coking due to pre-cracking at the passage outside surface and enhanced chemical coking at the passage inside surface is highest for a configuration represented by example 4(a). The resulting passage surface temperatures of example 4(c) are in between example 4(a) and 4(b), but closer to 4(b). At the cold end of the assembly the lowest passage inside temperatures are expected for example 4(a) and 4(c), while example 4(b) exhibits higher passage inside temperatures. For the examples 4(a) and 4(c) the distance to the temperature, below which risk of enhanced condensation coking increases, is lowest. Consequently, example 4(b) has the highest safety against enhanced condensation coking and could be selected if this is the main target.

[0156] With respect to the passage inside effluent pressure drop, which has impact on the cracking selectivity, it is lowest for example 4(a), followed by example 4(c) and is significantly higher for example 4(b). The high effluent pressure drop in example 4(b) results from the significantly higher passage length compared to example 4(a) and 4(c)

TABLE E

Example	unit	4(a)	4(b)	4(c)
Heat transferred	[%]	100	100	100
Passage inside pressure drop	[%]	100	217	111
Passage metal temperatures				
max. inside passage	[°C]	674	609	617
max. outside passage	[°C]	654	605	613
min. inside passage	[°C]	309	435	310
Residence time	[%]	100	83	120
Cooling rate	[%]	100	120	79
Heat transfer surface	[%]	100	243	112

[0157] With respect to residence time and cooling rate, referred to a cooling of the effluent until a temperature of 650 °C, the best values are seen for the configuration of example 4(b), which due to the highest temperature differences between effluent and feed at the effluent inlet. However, taking into account the required and comparable high heat transfer surface of example 4(b) and the high passage metal temperatures seen for example 4(a) the configuration as defined for example 4(c) may be the best solution for the application case shown herein, if heat transfer surface is limited.

[0158] Generally, the skilled person will select from the configurations of examples 4(a) through 4(c) depending on requirements given by specific technical and economical boundary conditions.

[0159] Having now described some illustrative embodiments of the disclosure, it should be apparent to those skilled in the art that the foregoing is merely illustrative and not limiting, having been presented by way of example only. Numerous modifications and other embodiments are within the scope of one of ordinary skill in the art and are contemplated as falling within the scope of the disclosure. In particular, although many of the examples presented herein involve specific combinations of method acts or system elements, it should be understood that those acts and those elements may be combined in other ways to accomplish the same objectives. Those skilled in the art should appreciate that the parameters and configurations described herein are exemplary and that actual parameters and/or configurations will depend on the specific application in which the systems and techniques of the disclosure are used. Those skilled in the art should also recognize or be able to ascertain, using no more than routine experimentation, equivalents to the specific embodiments of the disclosure. It is, therefore, to be understood that the embodiments described herein are presented by way of example only and that, within the scope of any appended claims and equivalents thereto, the embodiments of the disclosure may be practiced other than as specifically described.

[0160] Furthermore, the scope of the present disclosure shall be construed to cover various modifications, combinations, additions, alterations, etc., above and to the above-described embodiments, which shall be considered to be within the scope of this disclosure. Accordingly, various features and characteristics as discussed herein may be selectively interchanged and applied to other illustrated and non-illustrated embodiment, and numerous variations, modifications, and additions further can be made thereto without departing from the spirit and scope of the present disclosure as set forth in the appended claims.

[0161] An example thermal energy recovery assembly A to recover thermal energy from hot reactor effluent to heat a feed to a gas fired reactor furnace, may include an inner passage having a first inlet configured to receive hot reactor effluent from a gas fired reactor furnace, and an outer passage disposed about the inner passage to enclose an outer passage about the inner passage. The outer passage may have a second inlet configured to receive a feed to the gas fired reactor furnace, and the outer passage may be configured to use the feed for the gas fired reactor furnace as a cooling medium to recover thermal energy from the hot reactor effluent prior to the feed being supplied to the gas fired reactor furnace. The outer passage may be configured to enhance heat transfer from the hot reactor effluent to the feed in the outer passage.

[0162] In some embodiments, hot reactor effluent may reach a first inlet via a gas inlet chamber or other connector. In some embodiments, cooling may be supplied to the gas inlet chamber or other connector. In some embodiments, the gas chamber may connect one or more than one cracking coil to one or more than one inner passage. In some embodiments, a header may be provided to connect the feed to more than one outer passage. In some embodiments, cooled cracked gas from more than one inner passage may be collected using a header. In some embodiments, heated feed from more than one outer passage may be combined via a header. In some embodiments, multiple annuli may be contained in a single mechanical device, which may receive hot effluent from multiple cracking coils via a gas inlet chamber or other connector, and cold feed from a feed header.

[0163] The example assembly A above, wherein the outer passage includes at least one heat transfer enhancement to enhance heat transfer from the inner passage to the outer passage.

[0164] The example assembly A above, wherein the outer passage includes a first stage, and the at least one heat transfer enhancement comprises one or more of a plate impingement, a piccolo impingement, turbulence promotion, or increased surface area.

[0165] In example assembly A above, heat transfer enhancement by impingement may refer to flow of fluid passing through the outer passage, whose average direction as it proceeds from inlet to outlet may be substantially parallel to the inner passage, being purposely directed to flow toward the inner passage, for example, using geometric features introduced into the outer passage. In some embodiments, this directed (impinging) flow may, for example, be perpendicular to the inner passage, or directed toward the inner passage at an angle greater than thirty degrees relative to an axis of the inner passage, while its velocity may be relatively greater than a superficial velocity of the outer-passage fluid (for example, the volumetric flow of the outer-passage fluid divided by the area of the annular cross-section between the inner and outer passage). In some embodiments, the geometric features that promote impingement may include, for example, nozzles and/or openings oriented toward the inner passage, and/or obstructions placed in a flow path that may redirect fluid from a direction that is more parallel to the inner passage more directly towards the outer surface of the inner passage. These example features may be implemented in a periodic fashion, for example, resulting in impingement zones that occur at intervals along the length and/or the circumference of the inner passage. Applicant has discovered that introduction of such impingement features may increase the rate of heat transfer relative to the rate that would be attained by parallel flow through the outer passage. Moreover, Applicant has discovered that for a suitable level of heat transfer enhancement, a ratio of a velocity of an impinging flow to the superficial velocity may be greater than two, greaterthan five, or greaterthan ten. The velocity of the impinging flow may be approximated, in the case of nozzles or openings, as the volumetric flow divided by the total flow area defined by the nozzles or openings, through which the flow is directed. Additionally, the heat transfer enhancement may be found to be more suitable at distances between the impingement-inducing feature (e.g., between nozzles or openings 54) and the inner passage that are from about the diameter to about twelve times the diameter of the nozzles or openings 54, or from about the diameter to about ten times the diameter, or from about two times the diameter to about eight times the diameter. Examples of impingement features may include plate impingement and/or piccolo impingement.

[0166] The example assembly A above, wherein the outer passage includes a plate impingement disposed between an upstream end and a downstream end. The plate impingement may include a first channel having a stage inlet at the upstream end being closed to flow at the downstream end. The plate impingement also may include a second channel having a stage outlet at the downstream end. The second channel may be disposed between the first channel and the inner passage. The plate impingement may further include a wall separating the first channel from the second channel. The wall may define openings to fluidly connect the first channel and the second channel. The plate impingement may be configured to receive feed through the stage inlet, flow feed from the first channel to the second channel via the openings of the wall to impinge onto an outer surface of the inner passage, and exhaust feed through the stage outlet of the second channel.

[0167] The example assembly A above, wherein the outer passage includes a piccolo impingement. The piccolo impingement may include an upstream divider disposed about the inner passage and within the outer passage, a downstream divider disposed about the inner passage and within the outer passage downstream of the upstream divider within outer passage. The downstream divider may define at least one stage outlet. The piccolo impingement also may include a chamber defined within the outer passage and about the inner passage between the upstream divider and the downstream divider, and piccolo passages parallel to or at an angle with respect to the inner passage, and/or may be straight, curved, or bent, and/or offset from the inner passage. The piccolo passages may extend through the chamber from the upstream divider to the downstream divider. The piccolo passages may include a stage inlet for receiving incoming feed, and a plurality of openings defined therein, and the openings may be oriented toward the outer surface of the inner passage. The piccolo impingement may be configured to receive feed from the stage inlets, flow feed from the piccolo passages into the chamber via the plurality of openings, impinge the flow onto the outer surface of the inner passage, and/or exhaust feed from the chamber via the at least one stage outlet.

[0168] The example assembly A above, wherein: the at least one stage includes a first stage and a second stage; and one or more of: (1) the inner passage of the first stage has a first outlet and is configured to flow hot reactor effluent from the first inlet to the first outlet, the outer passage of the first stage has a second outlet and is configured to flow feed from the second inlet to the second outlet, and the second inlet of the first stage is adjacent the first outlet of the first stage and the second outlet of the first stage is adjacent the first inlet of the first stage; (2) the second stage includes at least one heat transfer enhancement including one or more of a plate impingement, a piccolo impingent, turbulence promotion, or increased surface area, the second stage being in series with the first stage; or (3) the second stage including an inner passage having a first inlet and a first outlet and is configured to flow reactor effluent from the first inlet of the second stage to the first outlet of the second stage; an outer passage having a second inlet and a second outlet and is configured to flow feed from the second inlet of the second stage to the second outlet of the second stage; and the second inlet of the second stage is adjacent the first inlet of the second stage and the second outlet of the second stage is adjacent the first outlet of the second stage.

[0169] The example assembly A above, wherein the at least one heat transfer enhancement of the first stage includes first impingement holes having a first diameter and the at least one heat transfer enhancement of the second stage includes second impingement holes having a second diameter, the second diameter being different from the first diameter.

[0170] The example assembly A above, wherein the inner passage includes a heat transfer enhancement.

[0171] The example assembly A above, wherein the inner passage has a first outlet and configured to flow hot reactor effluent from the first inlet to the first outlet, the outer passage having a second outlet and configured to flow feed from the second inlet to the second outlet, and one of: the second inlet is adjacent the first outlet and the second outlet is adjacent the first inlet; or the first inlet is adjacent second inlet and the first outlet is adjacent the second outlet.

[0172] The example assembly A above, wherein the thermal energy recovery assembly includes a plurality of inner passages parallel with one another with each inner passage disposed within an outer passage, each outer passage having one or more at least one of a plate impingement, a piccolo impingement, or turbulence promotion to enhance heat transfer from the inner passage to an outer passage defined within the outer passage. In some embodiments, the thermal energy recovery assembly may include a plurality of inner passages parallel with one another, with each inner passage disposed within an outer passage, and with the outer passage and optionally the inner passage having one or more heat transfer enhancements to enhance heat transfer from the inner passage to an outer passage defined within the outer passage.

[0173] The example assembly A above, wherein the thermal energy recovery assembly is configured: to cool the hot reactor effluent at a rate of at least 2.5 degrees Kelvin/millisecond, at least 3.5 degrees Kelvin/millisecond, at least 4.5 degrees Kelvin/millisecond, at least 5 degrees Kelvin/ms, or at least 5.5 degrees Kelvin/ms, for example, where the cooling rate may be defined as the inlet temperature of the hot reactor effluent (in degrees K) minus 923 K, divided by the residence time required for cooling from the temperature of the hot reactor effluent to 923 K, unless the inlet temperature of the hot reactor effluent (in degrees K) is less than 923 K or the temperature of the cooled reactor effluent is greater than 923K, in which case the cooling rate may be defined as the inlet temperature of the hot reactor effluent (in degrees K) minus the temperature of the cooled reactor effluent when it leaves the thermal energy recovery assembly, divided by the residence time of the effluent in the assembly. In some embodiments, the thermal energy recovery assembly may be configured such that a pressure drop of the hot reactor effluent passing through the thermal energy recovery assembly is less than 0.35 bar, less than 0.30 bar, less than 0.25 bar, or less than 0.20 bar; such that a residence time of the hot reactor effluent within the thermal energy recovery assembly is less than 100 milliseconds, less than 95 milliseconds, less than 90 milliseconds, less than 85 milliseconds, is less than 83 milliseconds, or is less than 80 milliseconds; or such that a pressure drop of the feed passing through the thermal energy recovery assembly is less than 15 bar, less than 12 bar, less than 10 bar, less than 8 bar, or less than 6 bar.

[0174] The example assembly A above, wherein the thermal energy recovery assembly is configured to preheat the feed to at least 350° Celsius, at least 375° Celsius, at least 400° Celsius, at least 425° Celsius, at least 450° Celsius, at least 475° Celsius, at least 500° Celsius, at least 525° Celsius, at least 550° Celsius, at least 575° Celsius, at least 600° Celsius, at least 625° Celsius, or at least 650° Celsius.

[0175] The example assembly A above, wherein the hot reactor effluent enters the thermal energy recovery assembly at a temperature greater than 575 ° Celsius, greater than 600° Celsius, greater than 610° Celsius, greater than 620°

Celsius, greaterthan 630° Celsius, greaterthan 640° Celsius, or greater than 650° Celsius.

[0176] The example assembly A above, wherein oxidant for the fired cracking furnace is preheated to a temperature greater than 180 °C, greaterthan 200 °C, greater than 250 °C, greater than 280 °C in a single stage or multiple stages by using thermal energy obtained in a cracked gas quench in the form of raised steam or heated boiler feed.

[0177] The example assembly A above, wherein oxidant for the fired cracking furnace is preheated to a temperature greater than 400 °C, greaterthan 550 °C, greater than 600 °C, greater than 700 °C, greaterthan 780 °C in a single stage or multiple stages against flue gas heat from combustion of a fuel gas with the said oxidant.

[0178] The example assembly A above, wherein oxidant is preheated in multiple steps to temperatures greater than 400 °C, greater than 550 °C, greater than 600 °C, greater than 700 °C, greater than 780 °C by a combination of the above mentioned methods

[0179] The example assembly A above, wherein preheated oxidant at temperatures greaterthan 400 °C, greaterthan 550 °C, greaterthan 600 °C, greaterthan 700 °C, greaterthan 780 °C is combusted with hydrogen or a hydrogen rich stream in the radiant zone of a fired cracking furnace to supply heat to the reaction zone.

[0180] A furnace assembly for heating a feed to provide a hot reactor effluent may include the example thermal energy recovery assembly A above; and a highly efficient and low emission gas-fired cracking furnace including a reaction zone configured to heat a feed to a cracking temperature thereof of one or more of ethane, propane, butane, condensate, light naphtha, heavy naphtha, gas oil, pyrolysis oil, materials derived from processing refinery streams, Fischer-Tropsch products, plastic waste, or biofeedstocks.

[0181] A method B to produce olefins may include supplying a reaction feed to an outer passage of a thermal energy recovery assembly, and heating the reaction feed in the outer passage of the thermal energy recovery assembly to output a preheated reaction feed. The example method B also may include supplying the preheated reaction feed to a highly efficient and low emission gas-fired cracking furnace comprising a reaction zone to heat the preheated reaction feed, and cracking the preheated reaction feed in the reaction zone to output hot reactor effluent comprising cracked hydrocarbons and olefins. The example method B further may include supplying the hot reactor effluent to an inner passage of the thermal energy recovery assembly, and supplying additional reaction feed to the outer passage of the thermal energy recovery assembly. The example method B also may include heating the additional reaction feed by transferring heat from the hot reactor effluent to the additional reaction feed via the thermal energy recovery assembly.

[0182] The example method B above, wherein one or more of: (1) supplying the hot reactor effluent to the inner passage of the thermal energy recovery assembly includes quenching the hot reactor effluent via heat transfer to the additional reaction feed; or (2) heating the reaction feed in the outer passage of the thermal energy recovery assembly comprises preheating the reaction feed via heat transfer to the reaction feed from the hot reactor effluent. The example method B above, further including enhancing the heat transfer to the additional reaction feed by providing heat transfer enhancements on one or more of the outer passage or the inner passage, the heat transfer enhancements including one or more of plate impingement, piccolo impingement, or turbulence promotion.

[0183] The example method B above, wherein supplying the hot reactor effluent to the inner passage of the thermal energy recovery assembly includes supplying the hot reactor effluent to the inner passage of the thermal energy recovery assembly at a temperature of at least 350° Celsius, at least 375° Celsius, at least 400° Celsius, at least 425° Celsius, at least 450° Celsius, at least 475° Celsius, at least 500° Celsius, at least 525° Celsius, at least 550° Celsius, at least 575° Celsius, at least 600° Celsius, at least 625° Celsius, or at least 650° Celsius.

[0184] The example method B above, wherein heating the reaction feed in the outer passage of the thermal energy recovery assembly to output a preheated reaction feed comprises heating the reaction feed to a temperature of at least 350° Celsius, at least 375° Celsius, at least 400° Celsius, at least 425° Celsius, at least 450° Celsius, at least 475° Celsius, at least 500° Celsius, at least 525° Celsius, at least 550° Celsius, at least 575° Celsius, at least 600° Celsius, at least 625° Celsius, or at least 650° Celsius.

Claims

1. A method to produce olefins comprising preheating a reaction feed, firing a conversion reactor, subjecting the reaction feed to a conversion in the conversion reactor, withdrawing a product gas from the conversion reactor, and cooling the product gas withdrawn from the conversion reactor, wherein

   - said preheating and said cooling comprises transferring heat from said product gas or a part thereof to said reaction feed or a part thereof using a thermal energy recovery assembly comprising one or more inner passages and one or more outer passages coaxially surrounding said inner passage(s),
   - said preheating and said cooling further comprises passing said reaction feed or said part thereof through said outer passage(s) of said thermal energy recovery assembly and passing said product gas or said part thereof through said inner passage(s) of said thermal energy recovery assembly,

- said firing the reactor comprises providing an oxidator gas at an oxidator gas temperature level of more than 400 °C using an oxidator gas preheating system and combusting a fuel gas comprising hydrogen and/or one or more hydrocarbons, using said oxidator gas at said temperature level, and
- said thermal energy recovery assembly is configured to meet a set of operating constraints including a first temperature constraint relating to an outside temperature of a containment of said inner passage of said thermal energy recovery assembly and a second temperature constraint relating to an inside temperature of the containment of said inner passage of said thermal energy recovery assembly.

2. The method according to claim 1, wherein said first temperature constraint limits said outside temperature to a first temperature range and said second temperature constraint limits said inside temperature to a second temperature range.

3. The method according to claim 2, wherein the first temperature range is between 550 and 750 °C and/or the second temperature range is between 150 and 350 °C.

4. The method according to any of the preceding claims, wherein said thermal energy recovery assembly comprises one heat recovery stage or several heat recovery stages arranged in parallel or in series, wherein each of the several heat recovery stages is either provided in a countercurrent flow configuration or a cocurrent flow configuration, wherein in said countercurrent flow configuration said product gas or said part thereof and said reaction feed or said part thereof are passed in opposite directions through the heat recovery stage and in said cocurrent flow configuration said product gas or said part thereof and said reaction feed or said part thereof are passed in the same direction through the heat recovery stage.

5. The method according to claim 4, wherein said product gas or said part thereof is passed through one of said heat recovery stages which is provided in said cocurrent configuration before being further cooled.

6. The method according to claim 5, wherein said further cooling is performed using a different one of said heat recovery stages which is provided in said countercurrent flow configuration.

7. The method according to claim 5, wherein said further cooling is performed using a further thermal energy recovery assembly including or being provided as at least one of a tube-in-tube and shell-and-tube type heat exchanger and particularly being provided in a countercurrent configuration.

8. The method according to any one of the preceding claims, wherein said thermal energy recovery assembly comprises one or more heat transfer enhancement structures to enhance heat transfer from said inner passage(s) to said outer passage(s)

9. The method according to claim 8, wherein said heat transfer enhancement structure(s) is or are provided as, or include(s), at least one of an impingement structure, a turbulence promotion structure, a high-shear-inducing structure, and an increased surface area.

10. The method according to claim 9, wherein said heat transfer enhancement structure(s) is or are provided in the outer passage(s) of the thermal energy recovery assembly and/or in at least one heat recovery stage thereof.

11. The method according to any one of the preceding claims, wherein said oxidant preheating comprises a first heating step indirectly against heat of said product mixture or said part thereof using an intermediate heat carrier.

12. A thermal energy recovery assembly configured for use in a method to produce olefins comprising preheating a reaction feed, firing a conversion reactor, subjecting the reaction feed to a conversion in the conversion reactor, withdrawing a product gas from the conversion reactor, and cooling the product gas withdrawn from the conversion reactor, according to any one of claims 1 to 10.

13. An apparatus for producing olefins including a thermal energy recovery assembly according to claim 12, wherein the apparatus is adapted to preheat a reaction feed, to fire a conversion reactor, to subject the reaction feed to a conversion in the conversion reactor, to withdraw a product gas from the conversion reactor, and to cool the product gas withdrawn from the conversion reactor, wherein said apparatus is configured to perform at least a part of said preheating and said cooling by transferring heat from said product gas or a part thereof to said reaction feed or a part thereof using said thermal energy recovery assembly.

14. The apparatus according to claim 13, wherein said thermal energy recovery assembly comprises one or more inner passages and one or more outer passages coaxially surrounding said inner passage(s), wherein said apparatus is configured to perform said preheating and said cooling by passing said reaction feed or said part thereof through said outer passage(s) of said thermal energy recovery assembly and passing said reaction feed or said part thereof through said inner passage(s) of said thermal energy recovery assembly.

15. The apparatus according to claim 13 or 14, wherein said apparatus is further configured to perform said firing the reactor to comprise providing an oxidator gas at an oxidator gas temperature level of more than 400 °C using an oxidator gas preheating system and combusting a fuel gas comprising hydrogen using said oxidator gas at the fuel gas temperature level.

Fig. 1A

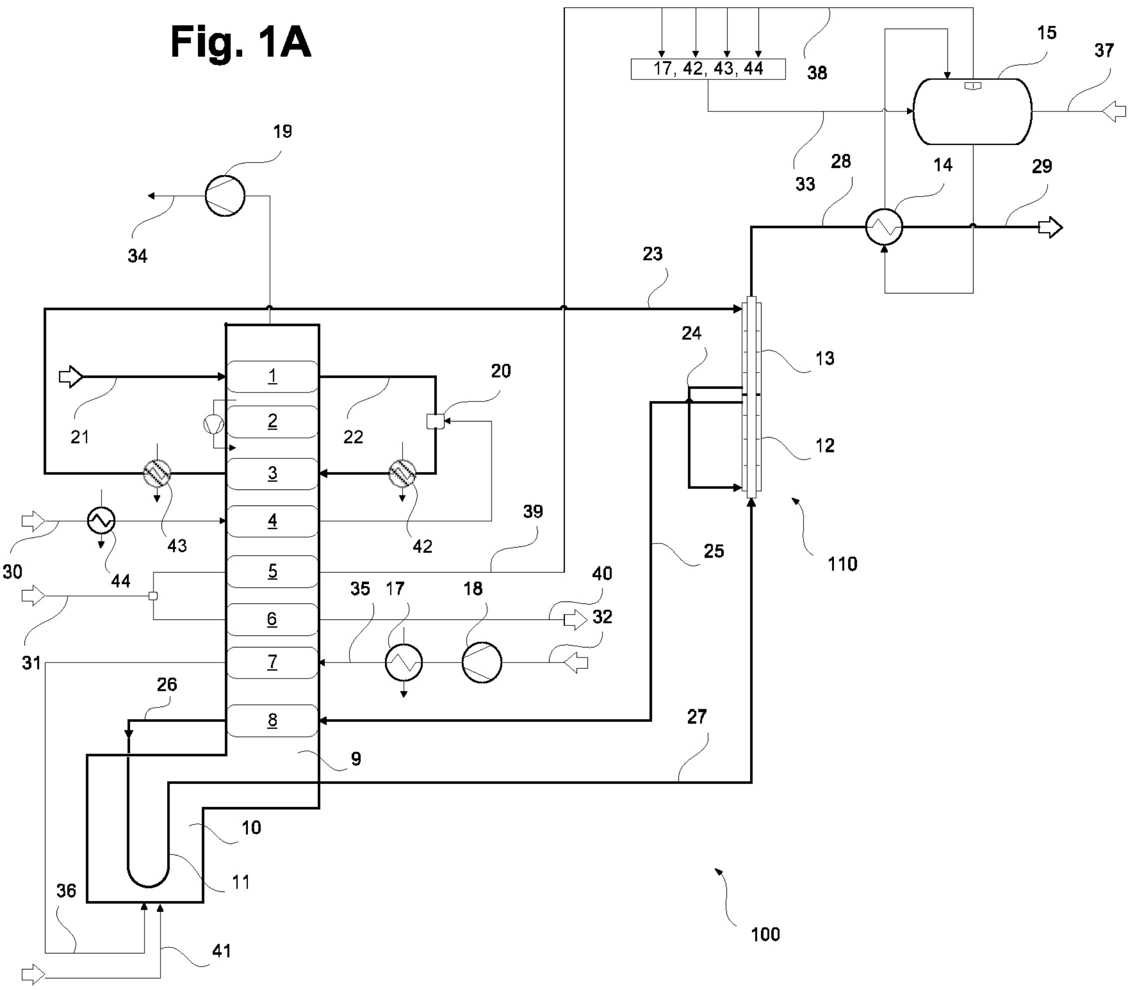


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Fig. 1B

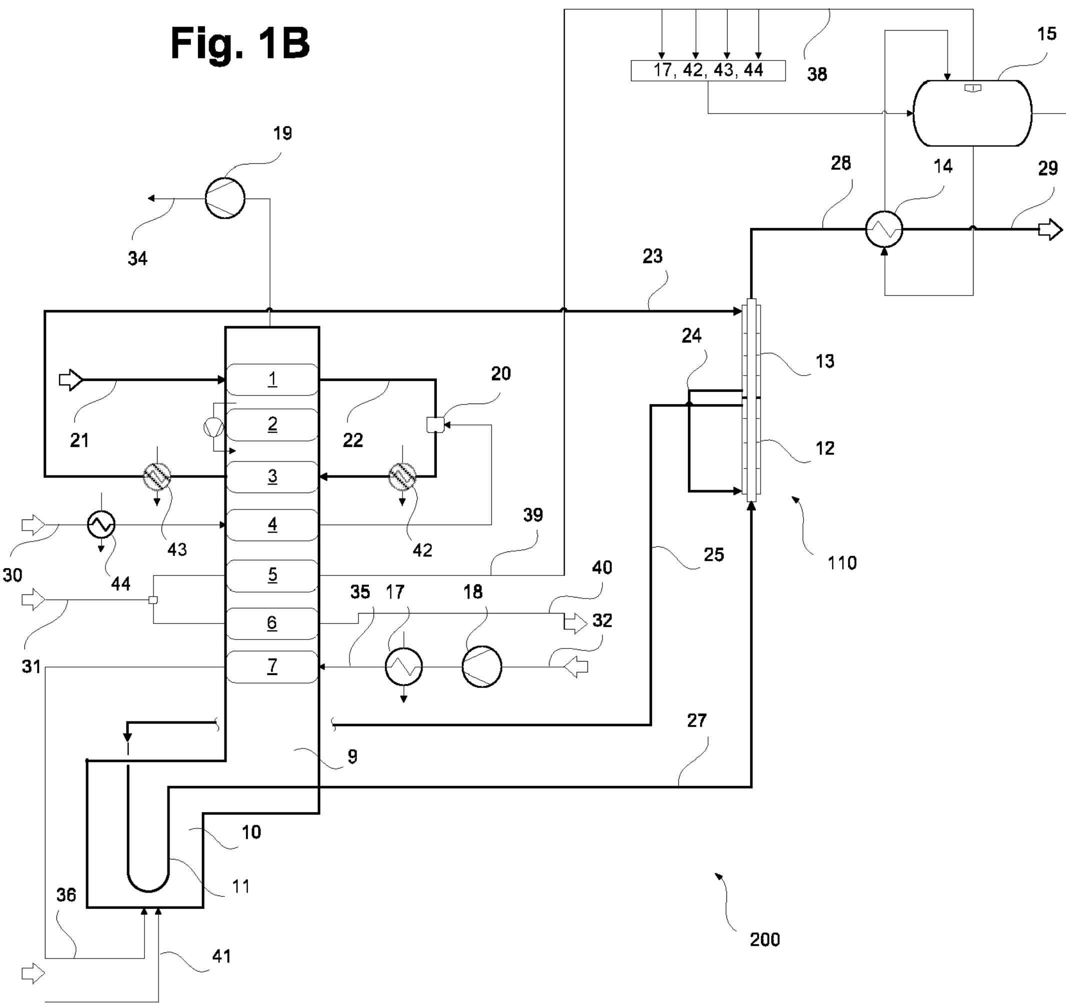
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Fig. 1C

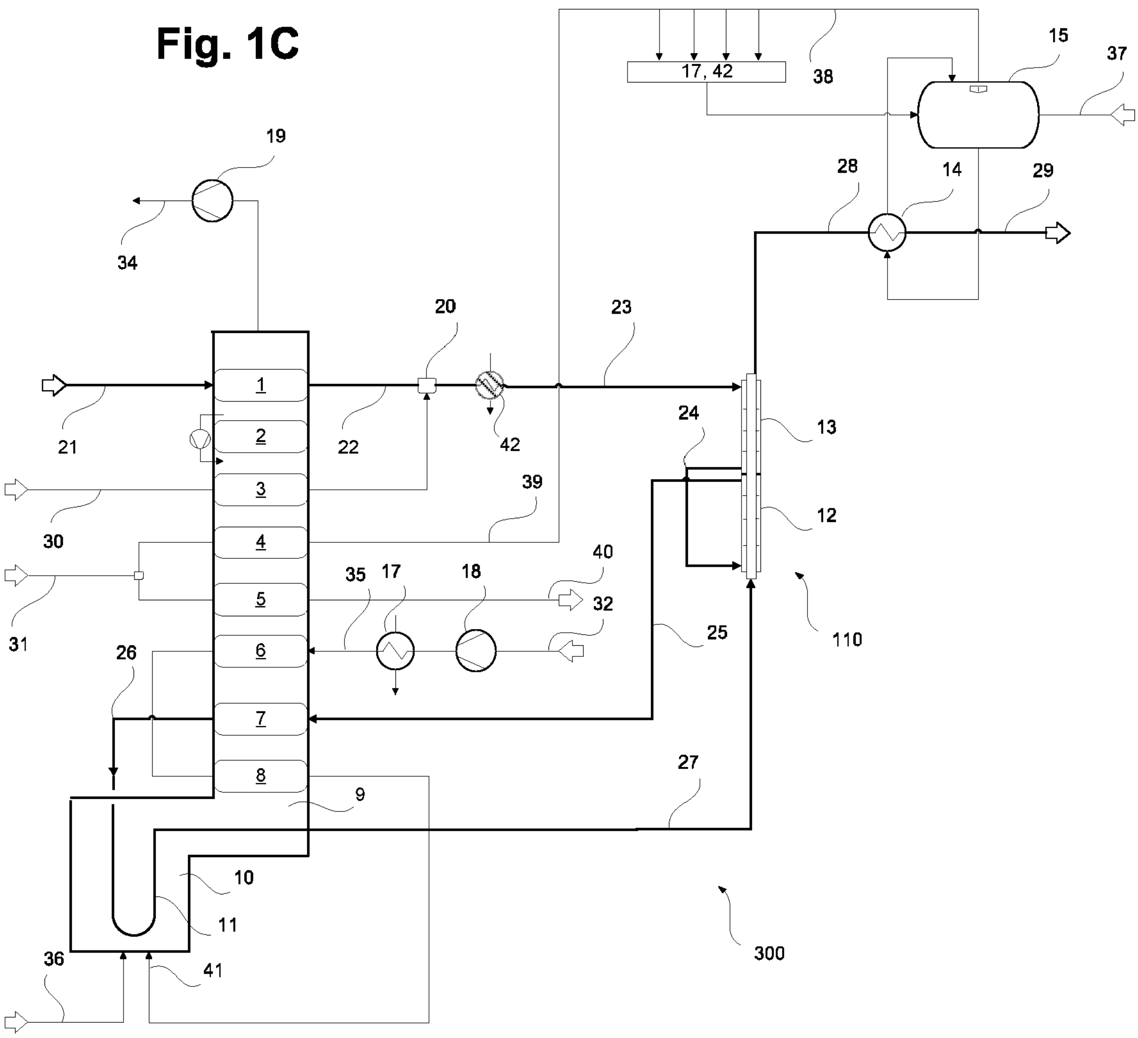
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Fig. 1D

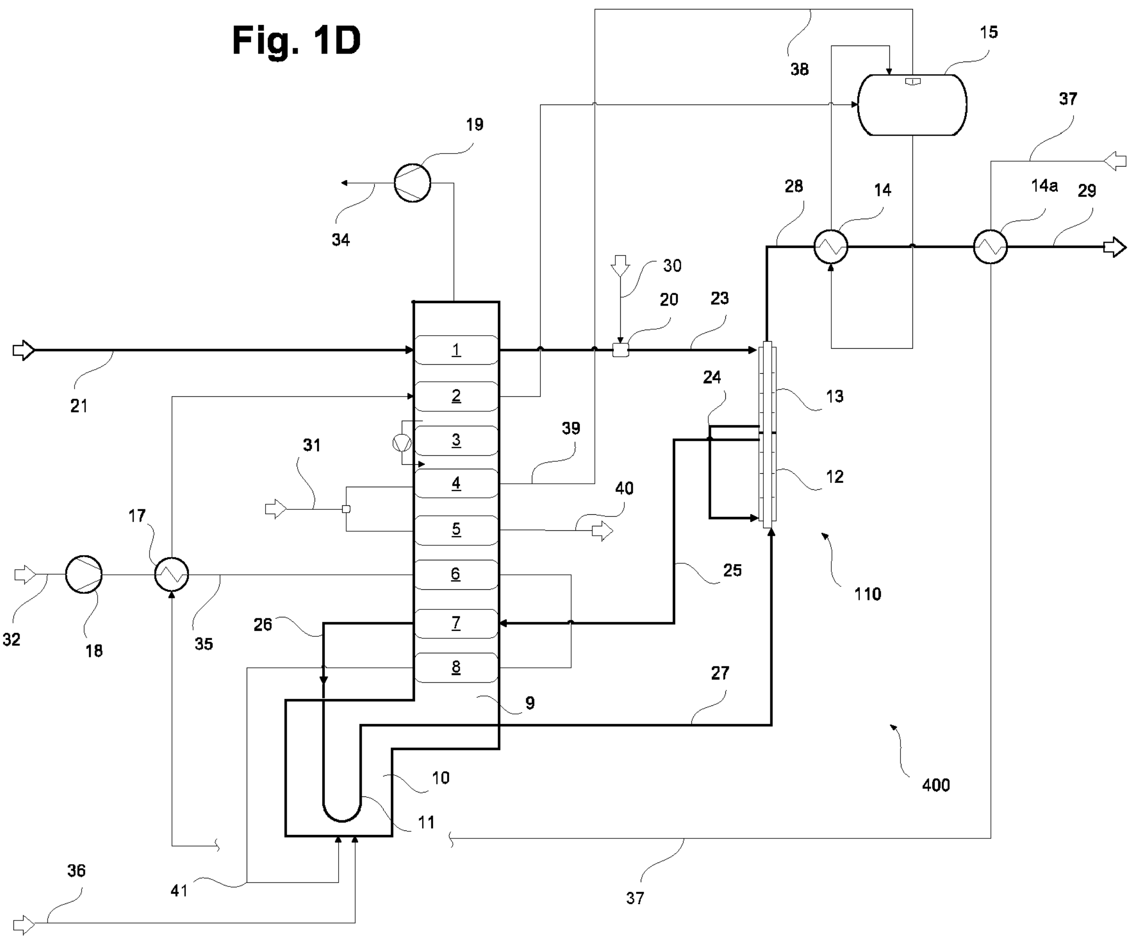

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Fig. 1E

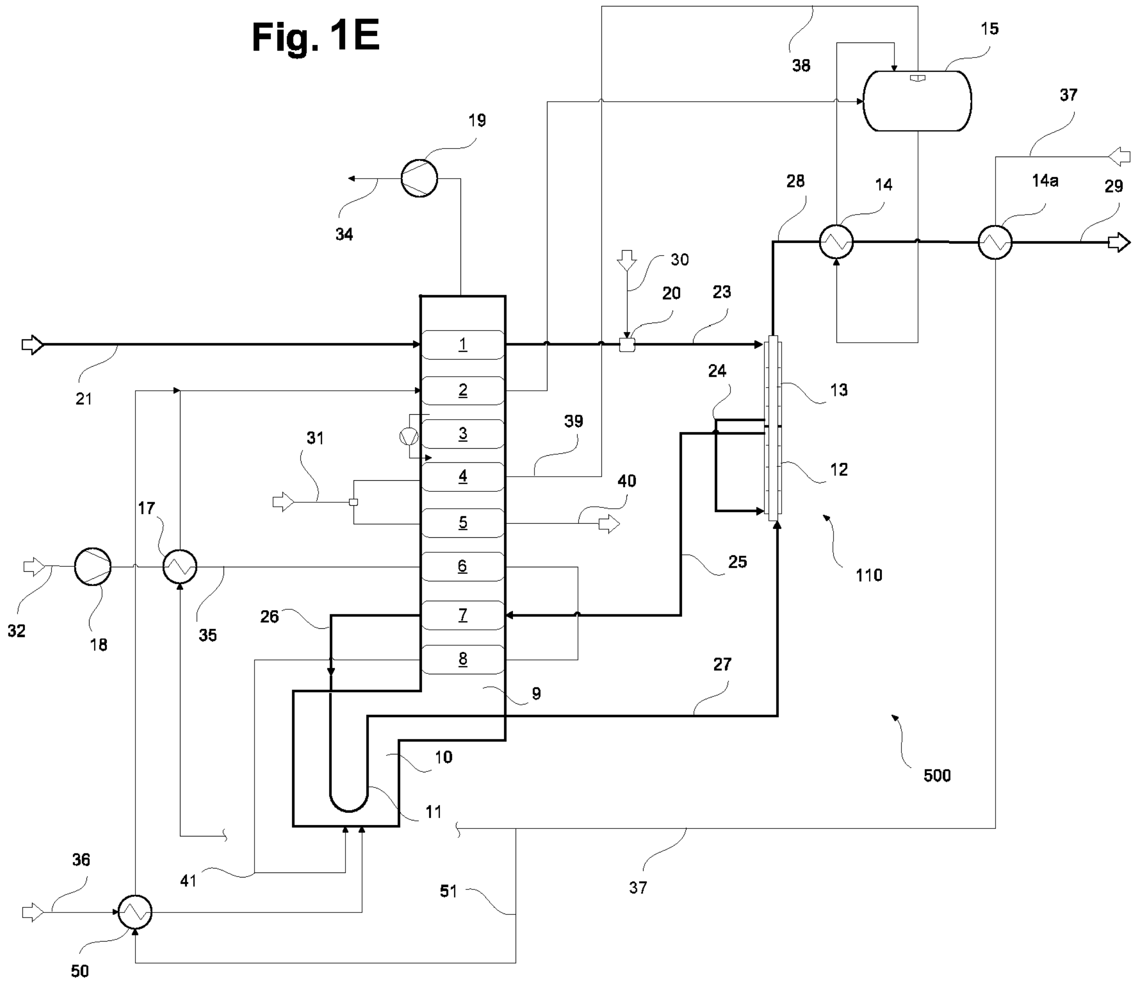
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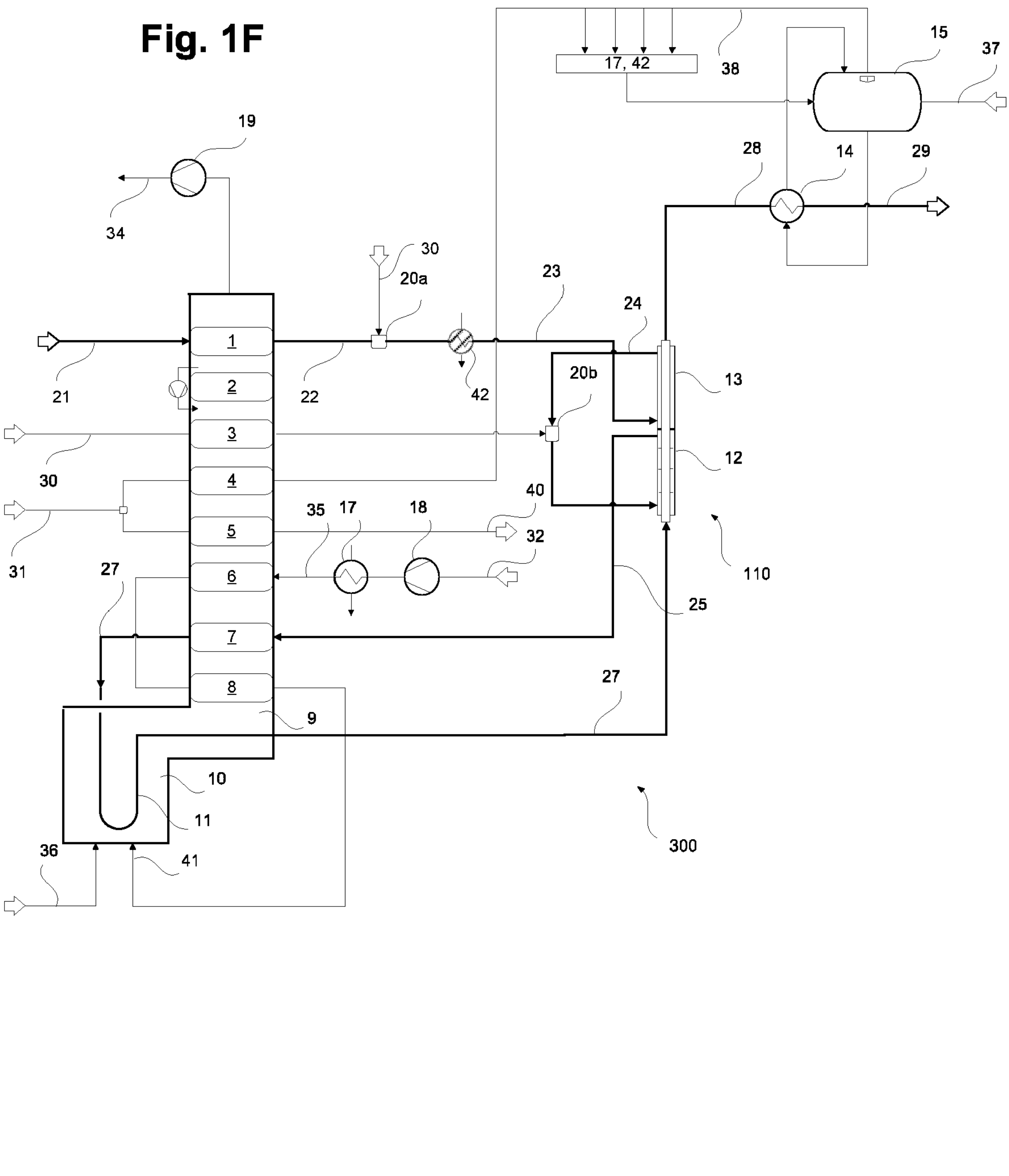
Fig. 1F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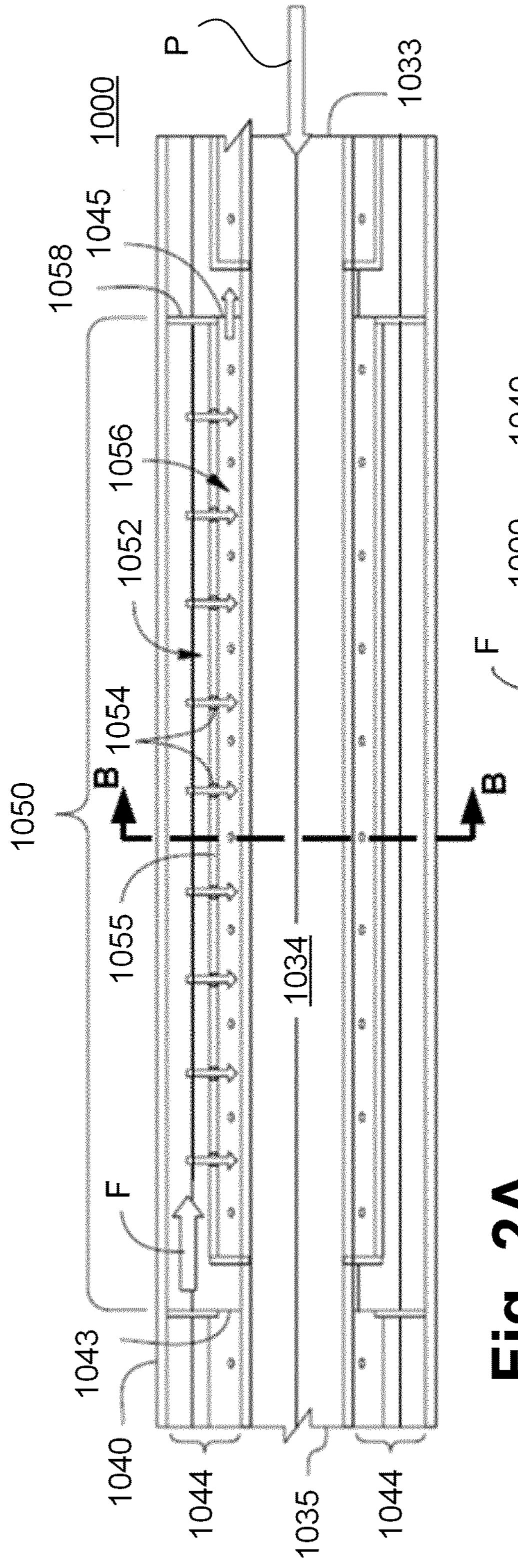

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Fig. 2A

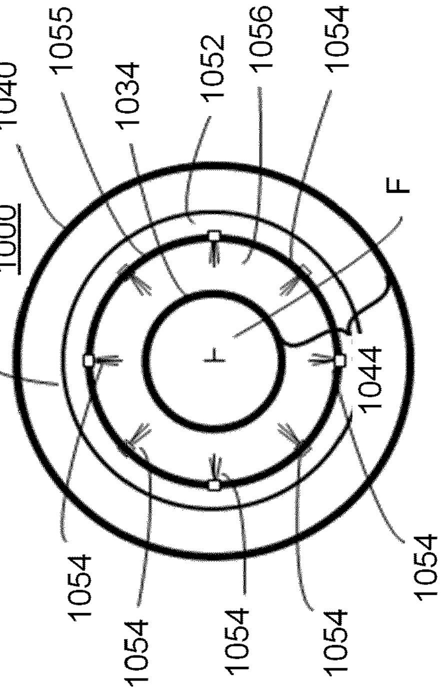

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Fig. 2B

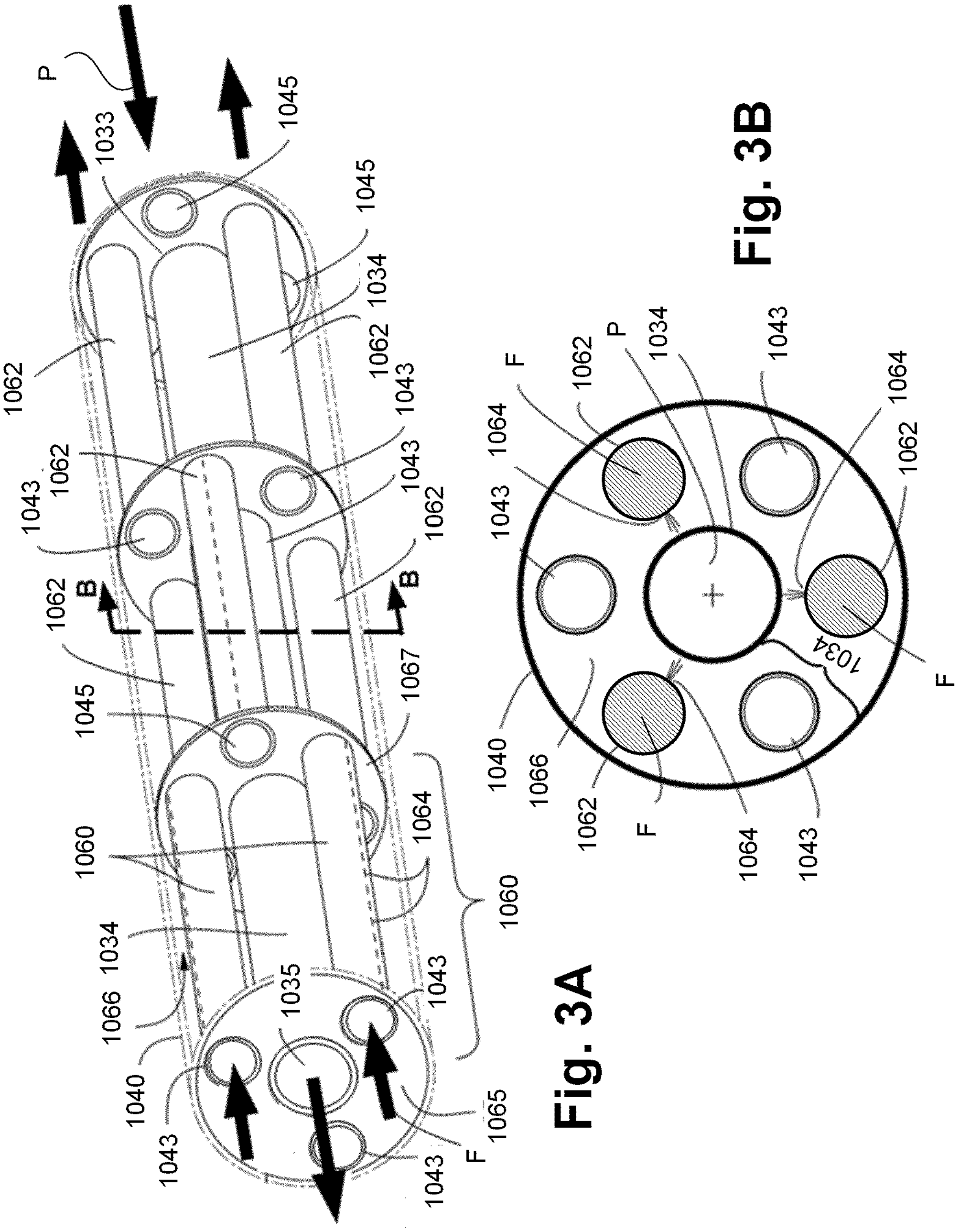
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Fig. 3A

Fig. 3B

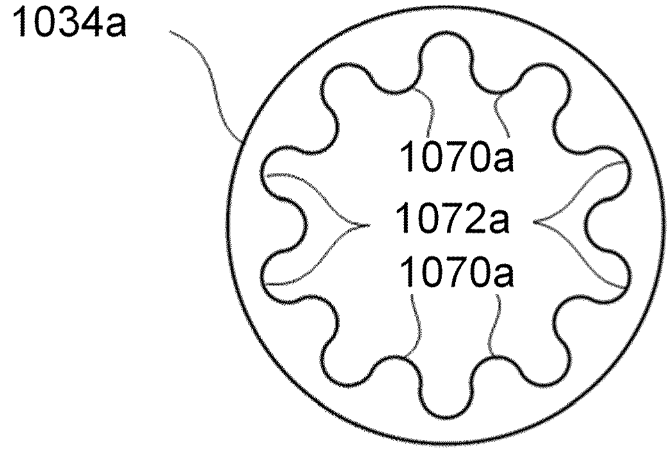


Fig. 4A

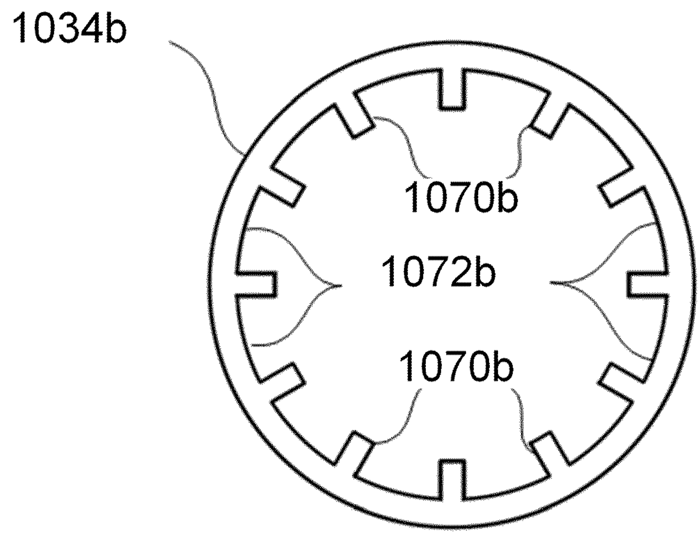


Fig. 4B

Fig. 5

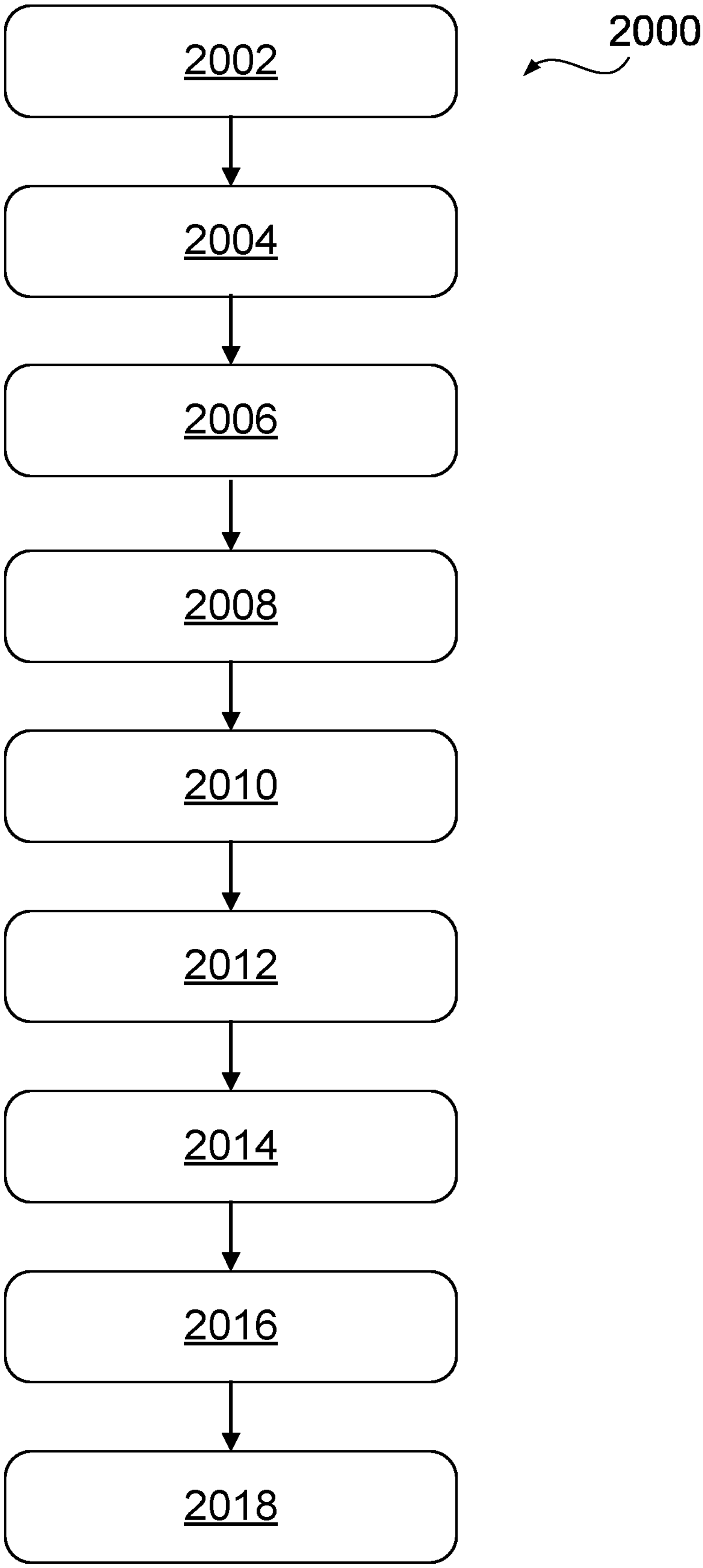


Fig. 6

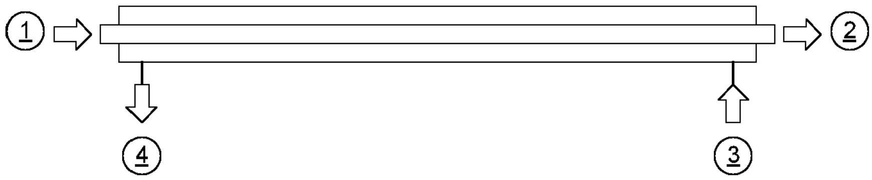


Fig. 7

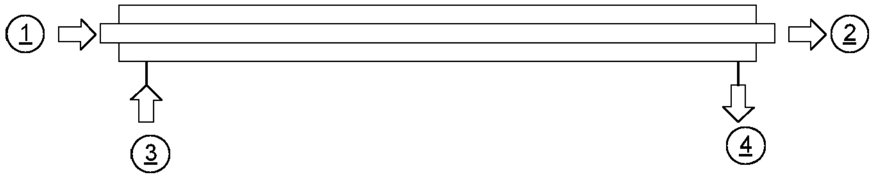


Fig. 8

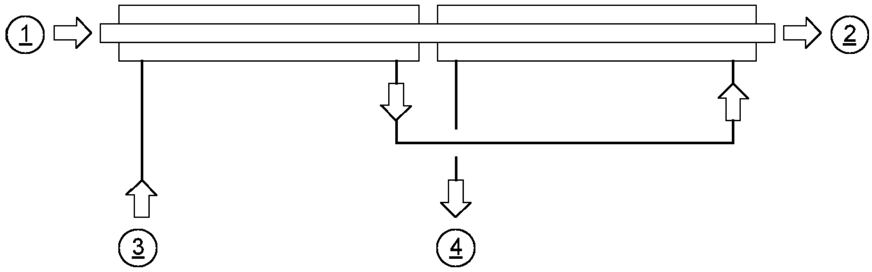


Fig. 9

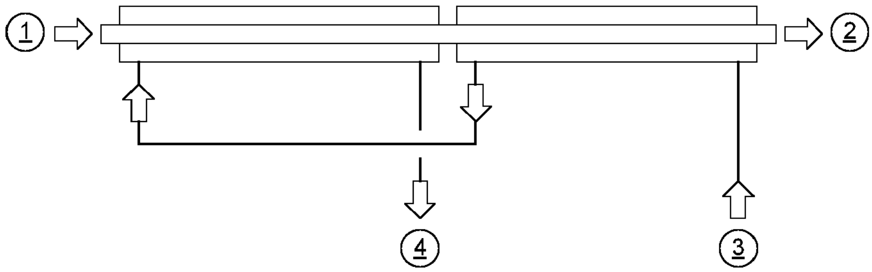
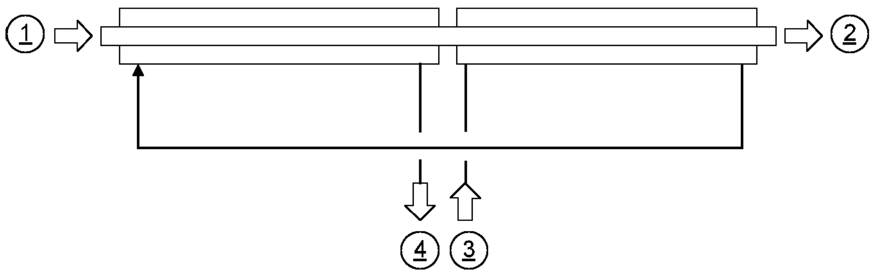


Fig. 10



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EUROPEAN SEARCH REPORT

Application Number
EP 23 16 5609

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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C10G
F28F
F28D
C07C

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	12 September 2023	Zuurdeeg, Boudewijn

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page 1 of 2

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EUROPEAN SEARCH REPORT

Application Number
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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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Place of search	Date of completion of the search	Examiner
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