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(54) SHELL-SIDE FLUID DISTRIBUTION IN COIL WOUND HEAT EXCHANGERS

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(57) ABSTRACT

Embodiments of the present invention provide improved shell-side fluid distribution in coil wound heat exchanger system and methods therefor. The fluid distribution system includes a system having a plurality of distribution arms having inner and outer cavities and valves to control the flow of shell-side fluid to control radial temperature profiles in a coil wound heat exchanger having multiple bundles of tubes.

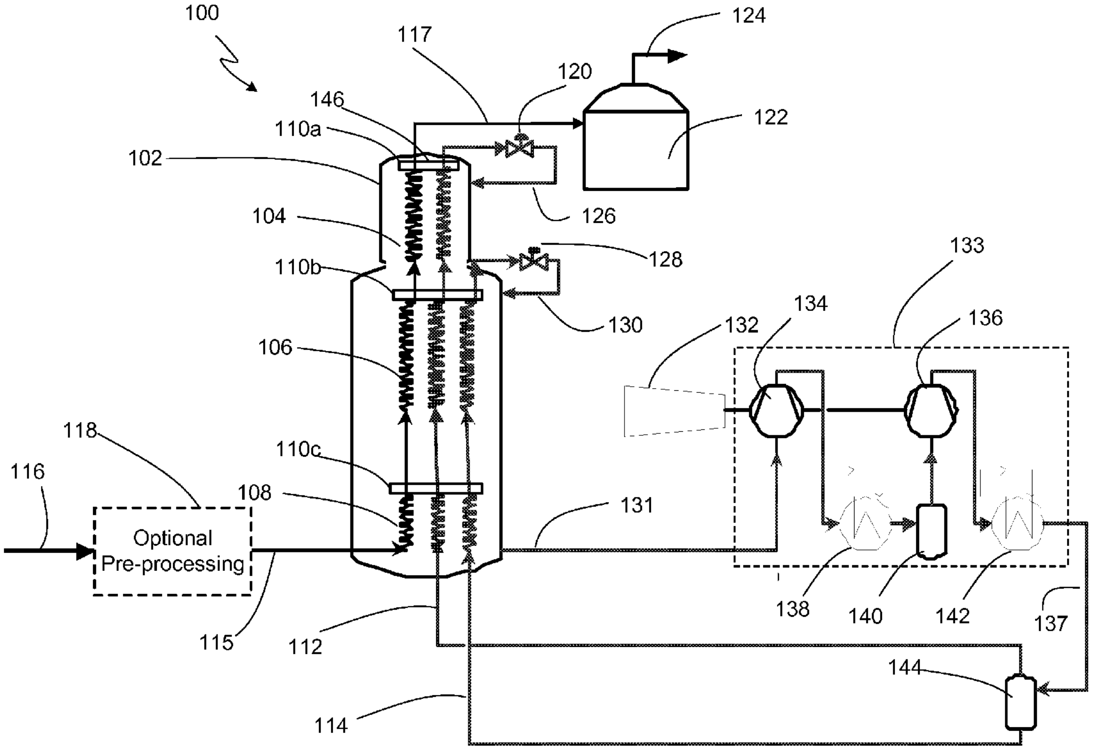
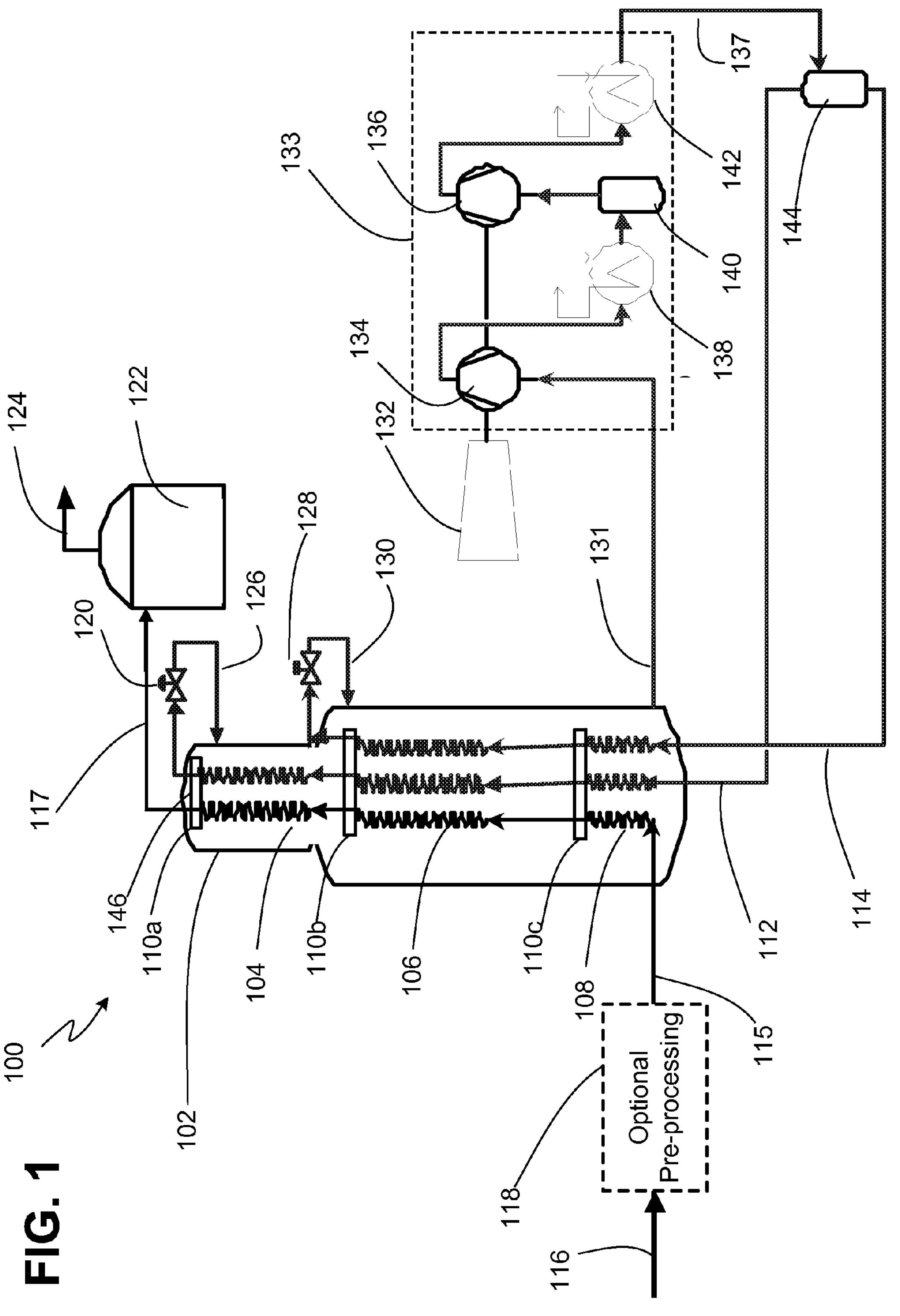


FIG. 1


100
102
104
106
108
110a
110b
110c
112
114
115
116
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Optional Pre-processing
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144
146

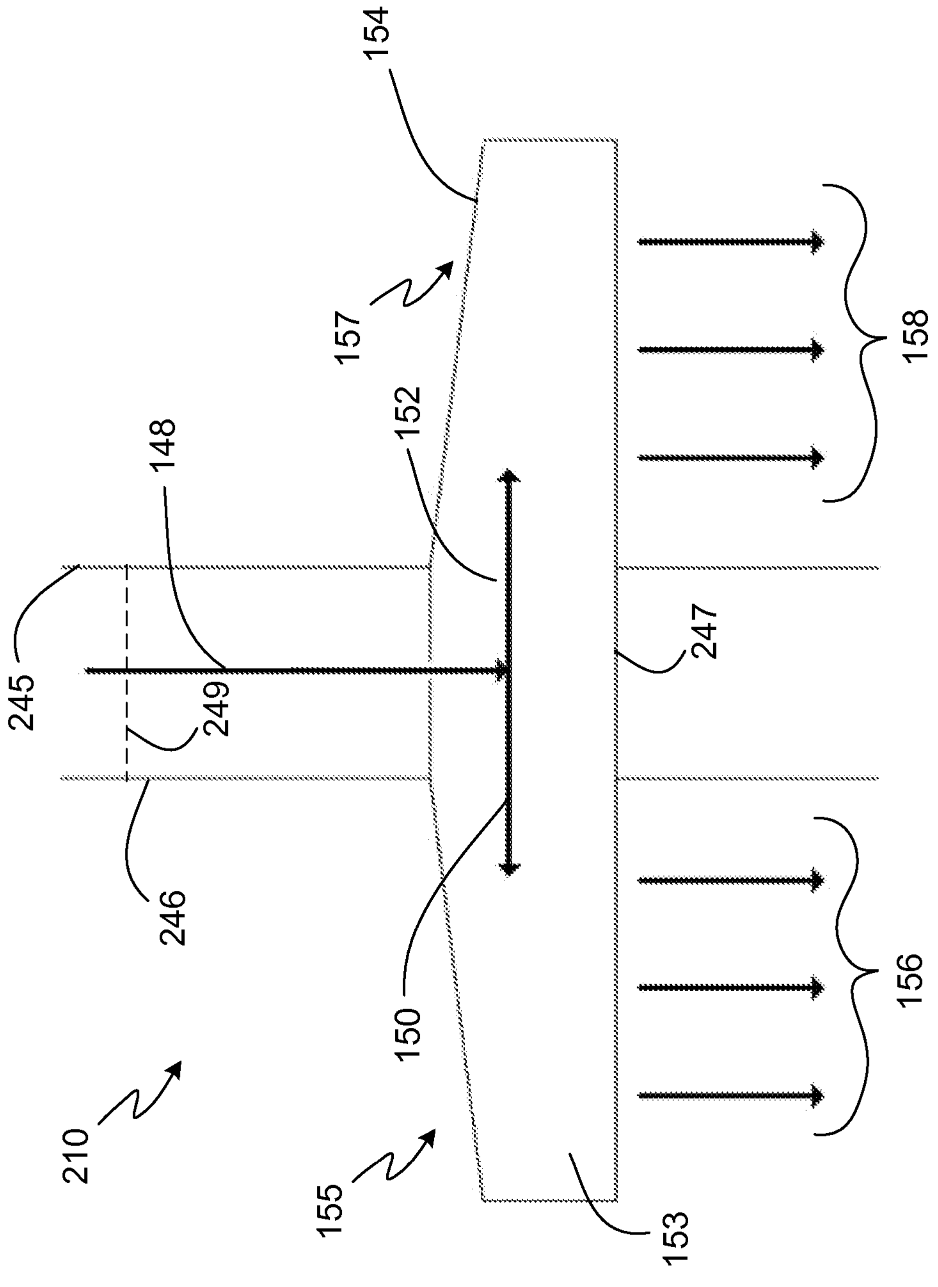
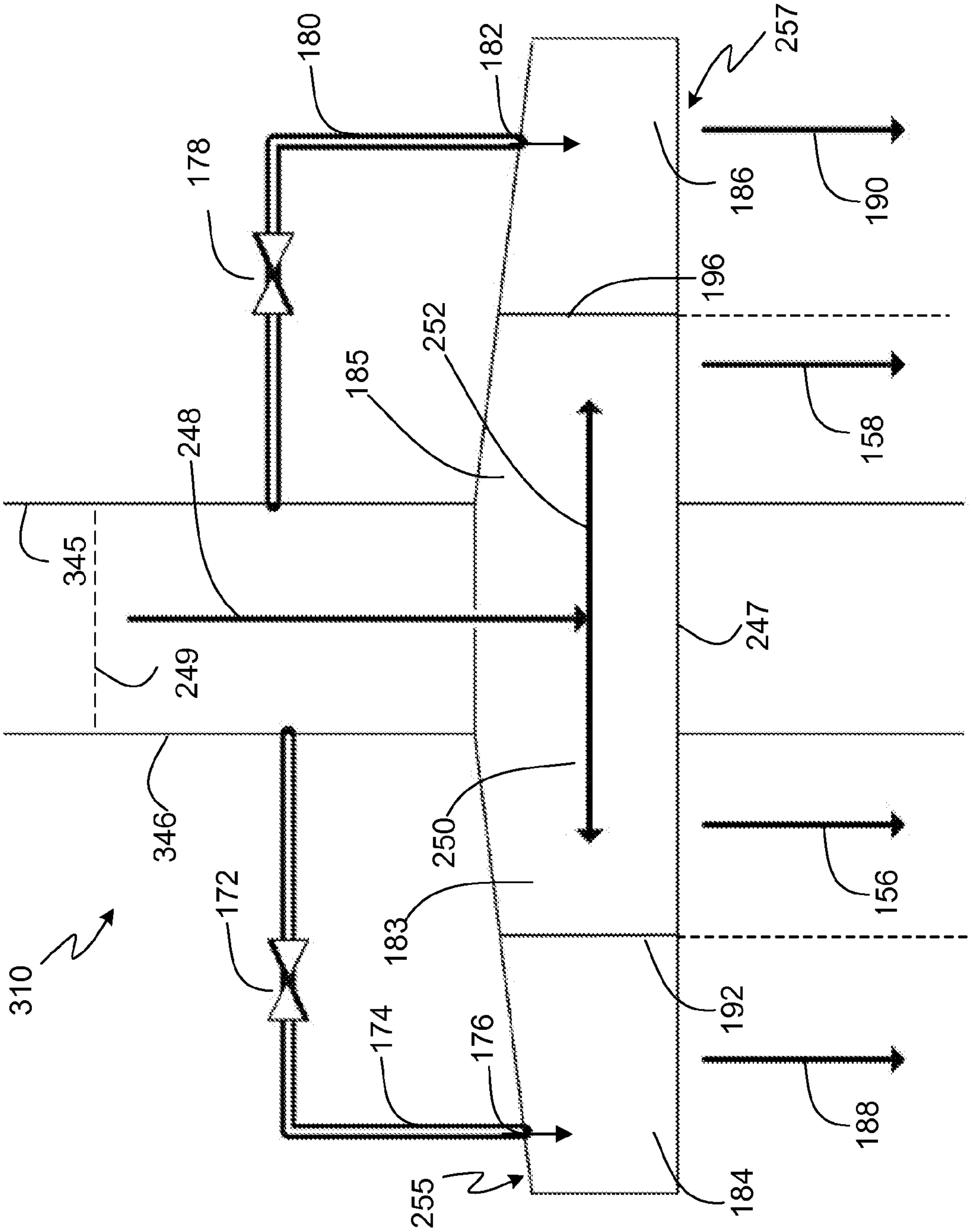


FIG. 2 (Prior Art)

FIG. 3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345
346
249
248
172
174
176
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FIG. 4

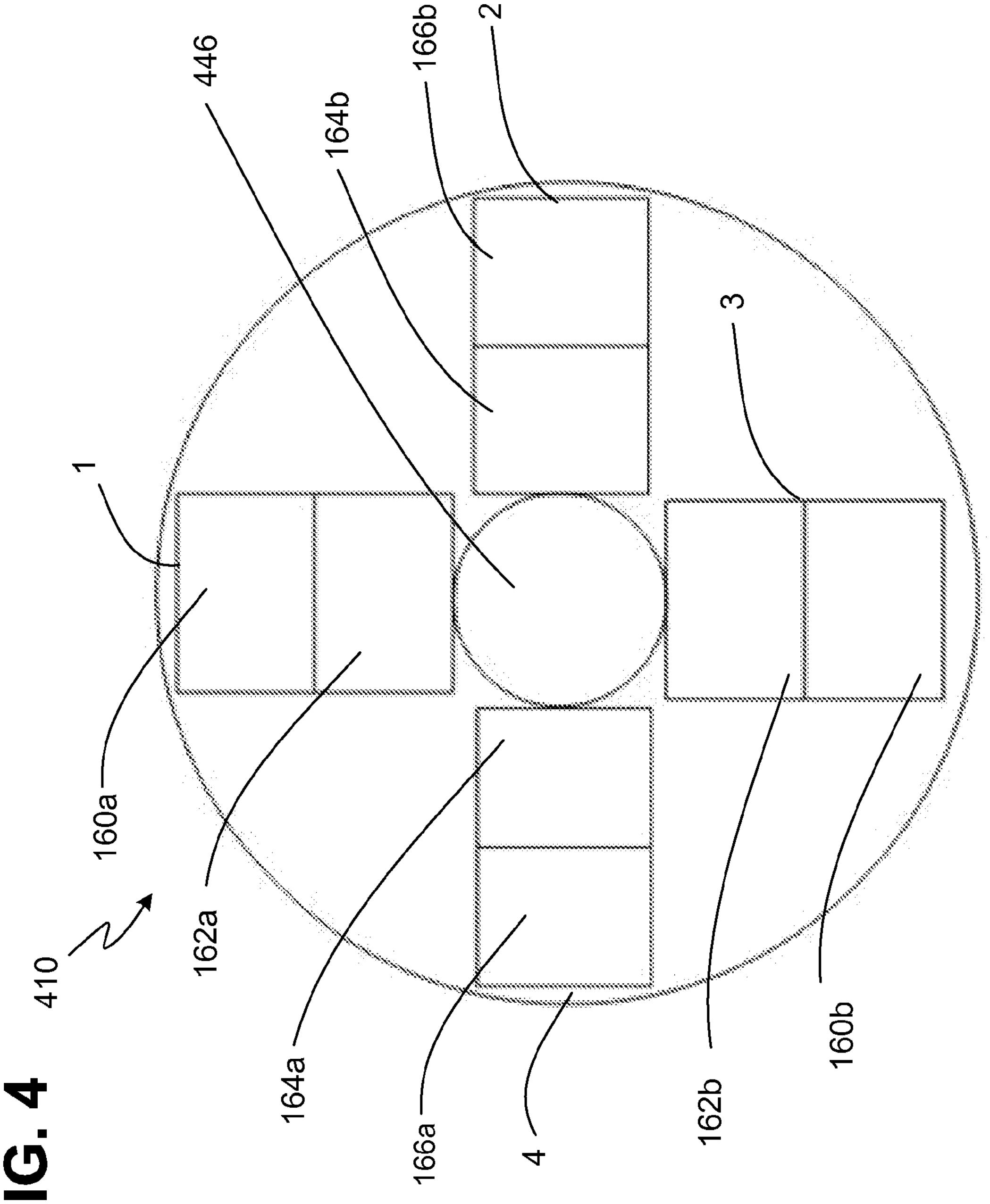


FIG. 5

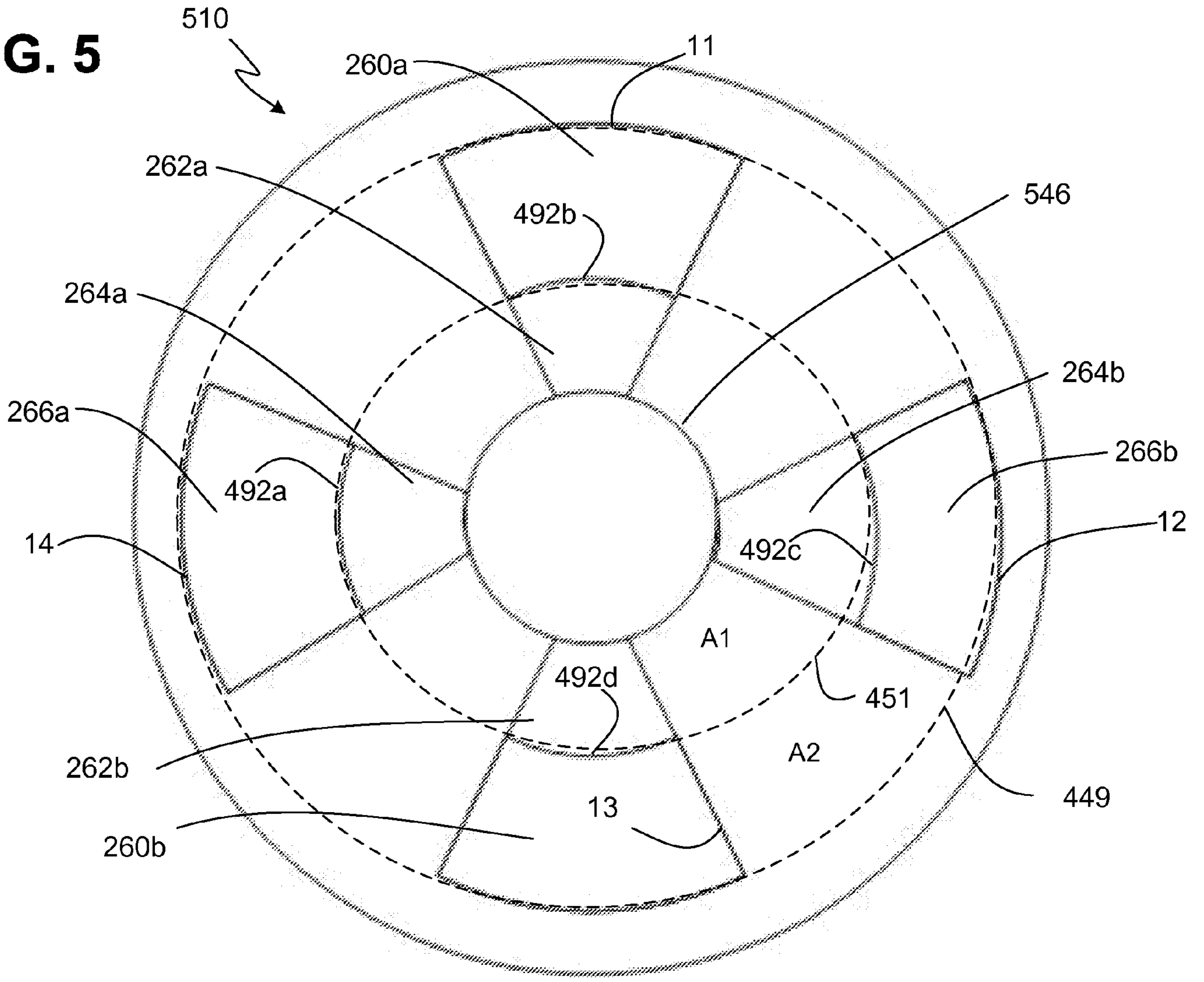

510
260a
11
262a
492b
546
264a
264b
266a
266b
492a
14
492c
12
A1
492d
451
262b
A2
449
13
260b

FIG. 6

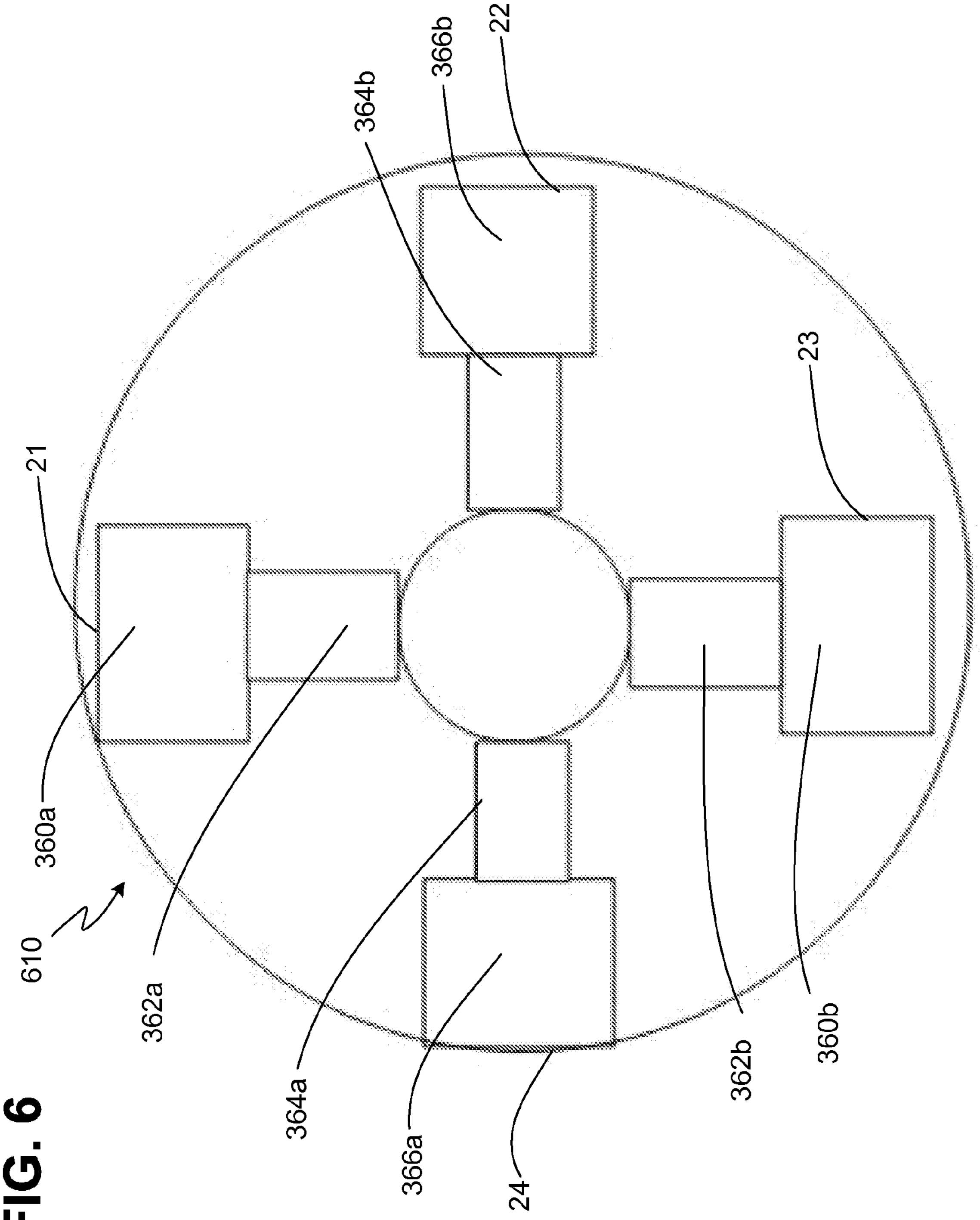
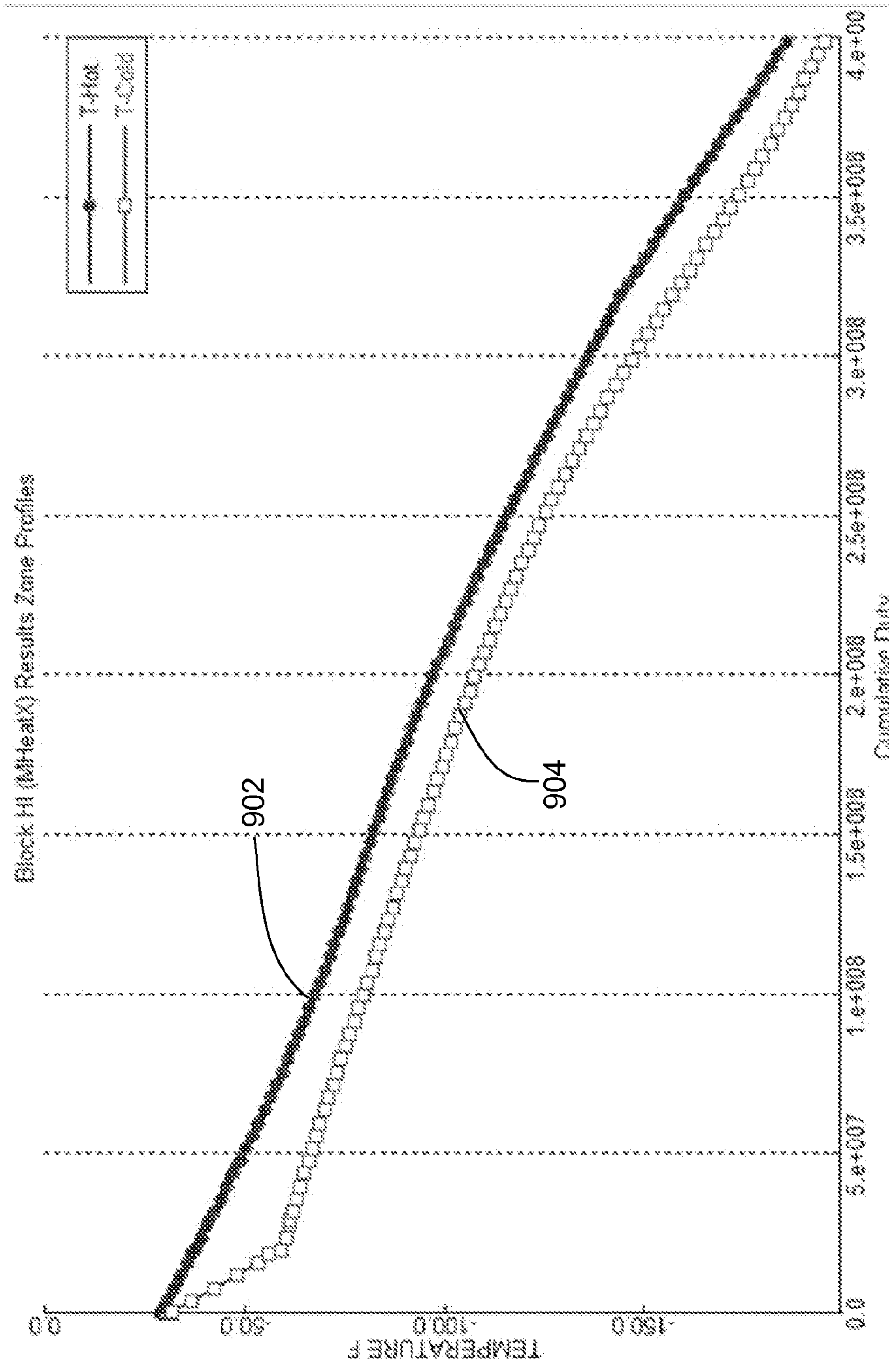


FIG. 7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-100.0
-150.0
Cumulative Duty
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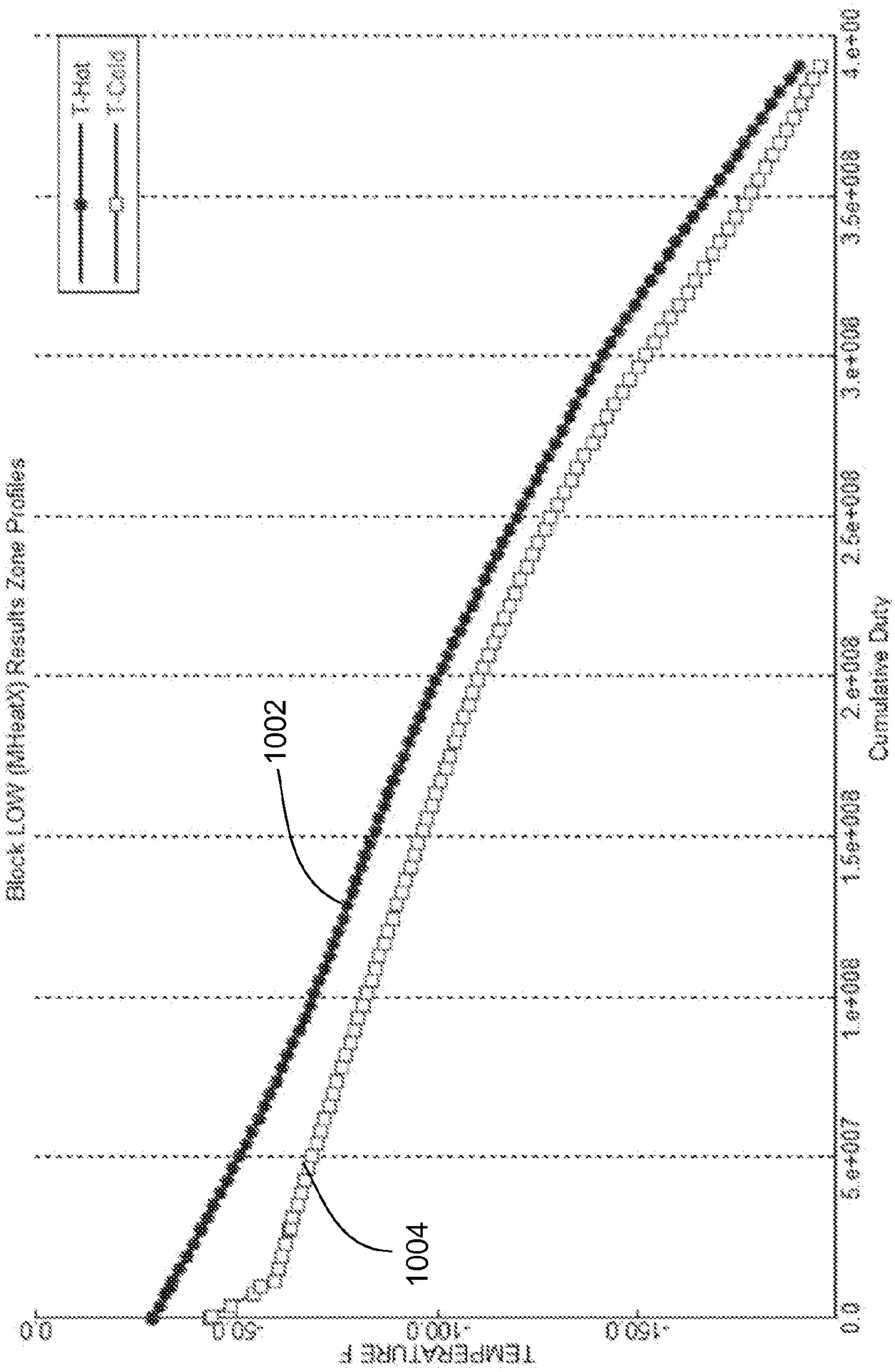
1.e+008
1.5e+008
2.e+008
2.5e+008
3.e+008
3.5e+008
4.e+008
T-Hot
T-Cold
902
904

FIG. 8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T-Cold
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1004
TEMPERATURE F
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-50.0
-100.0
-150.0
Cumulative Duty
0.0
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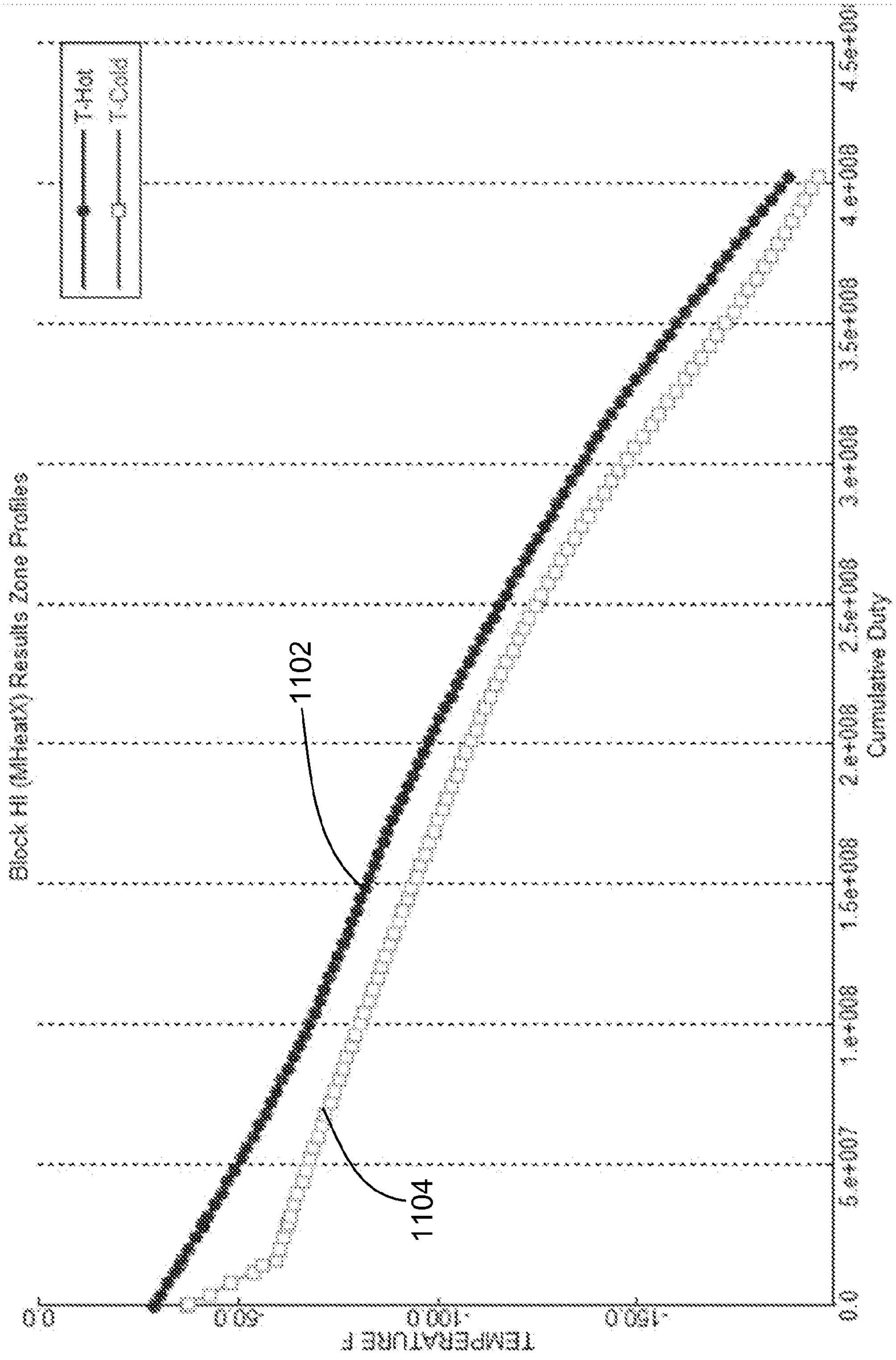
1.5e+008
2.e+008
2.5e+008
3.e+008
3.5e+008
4.e+008

FIG. 9


Block HI (MHeatX) Results Zone Profiles
T-Hot
T-Cold
1102
1104
TEMPERATURE F
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-100.0
-150.0
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1.e+008
1.5e+008
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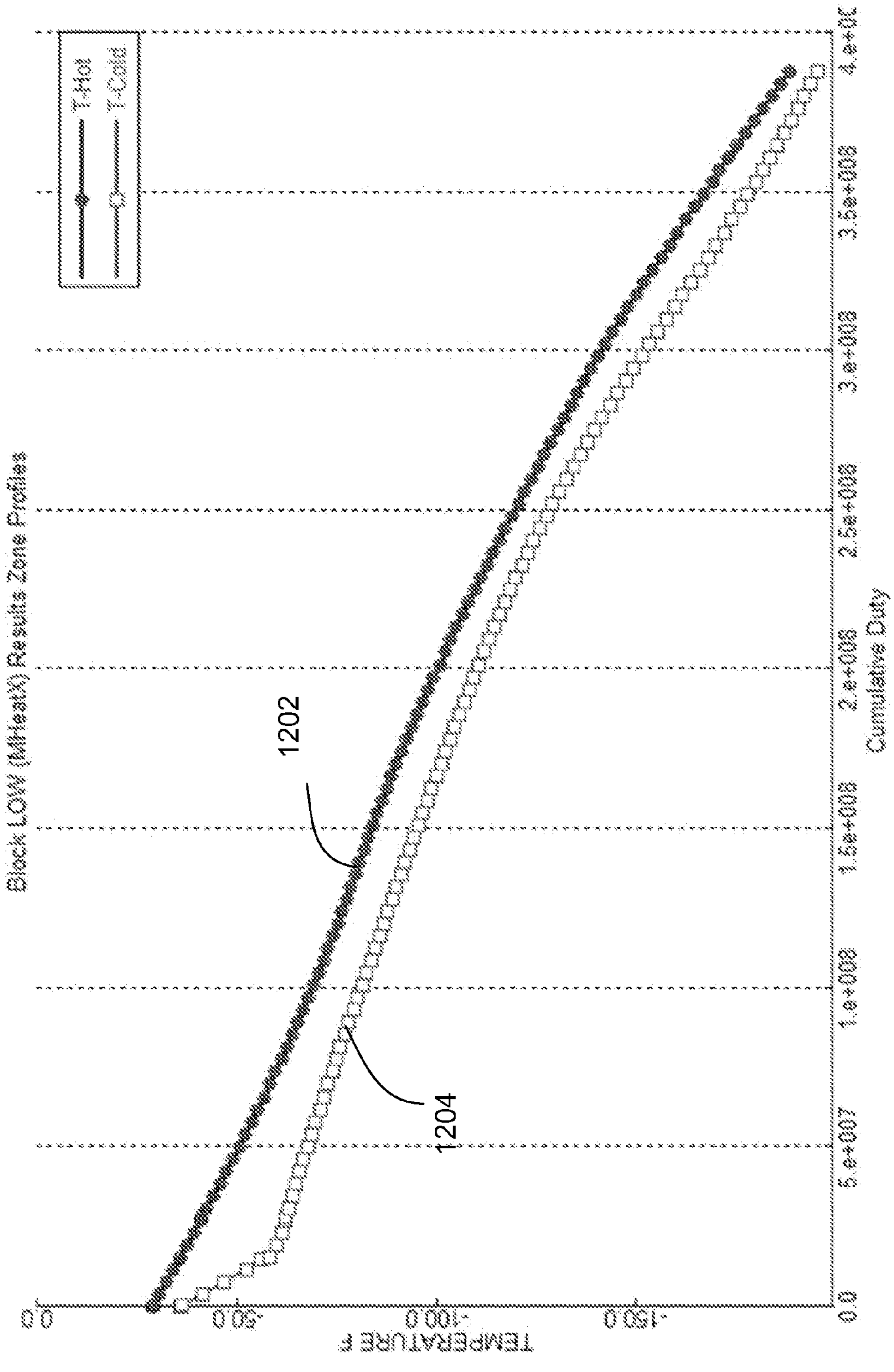
2.5e+008
3.e+008
3.5e+008
4.e+008
4.5e+008
Cumulative Duty

FIG. 10


Block LOW (MHeatX) Results Zone Profiles
T-Hot
T-Cold
TEMPERATURE F
0.0
-50.0
-100.0
-150.0
Cumulative Duty
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5.e+007
1.e+008
1.5e+008
2.e+008
2.5e+008
3.e+008
3.5e+008
4.e+00
1202
1204

SHELL-SIDE FLUID DISTRIBUTION IN COIL WOUND HEAT EXCHANGERS

BACKGROUND

[0001] Coil Wound Heat Exchangers (CWHEs) are often employed for natural gas liquefaction. CWHEs typically contain helically wound tube bundles housed within an aluminum or stainless steel pressurized shell. For Liquid Natural Gas (LNG) service, a typical CWHE includes multiple tube bundles, each having several tube circuits. Cooling might be provided using a variety of refrigerants, for example, a mixed refrigerant (MR) stream having a mixture of nitrogen, methane, ethane/ethylene, propane, butanes and pentanes is a commonly used refrigerant for many base-load LNG plants. The refrigeration cycle employed for natural gas liquefaction might be a cascade cycle, single mixed refrigerant cycle (SMR), propane-precooled mixed refrigerant cycle (C3MR), dual mixed refrigerant cycle (DMR), nitrogen or methane expander cycles, or any other appropriate refrigeration process. The composition of the MR stream is optimized for the feed gas composition and operating conditions.

[0002] Located at the top of each tube bundle within the exchanger shell is a distributor assembly that distributes the liquid refrigerant across the top of the tube bundle. It is important that the shell-side refrigerants and tube side flow is optimally distributed over all the layers of tubes in the tube bundles since mal-distribution of the liquid refrigerant might lead to uneven temperature profiles across the radius of the heat exchanger and a range of temperatures for the fluids exiting the tubes on the cold end of the tube bundles. This is especially pertinent to Floating Liquid Natural Gas (FLNG) facilities where sea conditions may lead to vessel motion which may in turn cause mal-distribution of the liquid refrigerant. Such mal-distribution of liquid refrigerant and resulting uneven heat transfer reduces the effectiveness of the heat exchanger and the efficiency of the liquefaction process.

[0003] Therefore, in the design of a CWHE, substantial effort is made, and cost incurred, to ensure proper distribution of fluids. For example, U.S. Patent Application Publication 2012/0261088 describes a sectioned heat exchanger with multiple liquid-tight tube bundles with separate tube-side and shell-side inlets and outlets with multiple sectioned distributor arms, such that each section of the arm corresponds to a tube bundle section. Radial temperature profiles are controlled by adjusting the tube-side and shell-side flowrates to each section. In effect, the application describes separate parallel heat exchangers that share a common refrigerant, but requires multiple tube bundle sections.

[0004] Thus, there is a need to provide a low cost (both in terms of heat exchange construction and operating costs) process to ensure optimal distribution of liquid refrigerant regardless of process conditions, for example, even under high vessel motion conditions in FLNG systems.

BRIEF SUMMARY OF

[0005] According to one embodiment of the present invention, a coil wound heat exchanger system is disclosed. In addition, several specific aspects of the systems and methods of the present invention are outlined below.

[0006] Aspect 1. A system for indirect heat exchange between a feed gas and a refrigerant, the system comprising:

> **[0007]** a feed gas conduit in flow communication with a supply of the feed gas;
>
> **[0008]** a shell defining a shell space;
>
> **[0009]** at least one tube bundle located in the shell space, each of the at least one tube bundle comprising a first set of tubes in fluid flow communication with the feed gas conduit, a central conduit, and a distributor assembly, the first set of tubes having a cold end and a warm end and being helically wrapped around a central mandrel, the distributor assembly having a plurality of arms located above the first set of tubes, each of the plurality of arms having a first cavity including a plurality of apertures, the first cavity being in direct fluid flow communication with the central conduit, the central conduit being in fluid flow communication with a supply of the refrigerant;
>
> **[0010]** wherein at least one of the plurality of arms further comprises a second cavity including a plurality of apertures and a separating wall located between the first and second cavities to inhibit fluid flow communication between the first and second cavities, the second cavity being in fluid flow communication with the central conduit only through a bypass conduit and a valve, the second cavity being located at a greater radial distance from the central mandrel than the first cavity.

[0011] Aspect 2. The system of Aspect 1, wherein the at least one tube bundle further comprises a second set of tubes having a cold end and a warm end, the second set of tubes being located below the plurality of arms, helically wrapped around the central mandrel, and in fluid flow communication with a first refrigerant conduit, the second set of tubes comprising the supply of the refrigerant to the central conduit.

[0012] Aspect 3. The system of any of Aspects 1 or 2, wherein the central conduit comprises the central mandrel and a plate located within the central mandrel comprises a lower end of the central conduit.

[0013] Aspect 4. The system of any of Aspects 1-3, wherein the first cavity has a first flow per unit bundle area and the second cavity has a second flow per unit bundle area and the second flow per unit bundle area is greater than the first flow per unit bundle area.

[0014] Aspect 5. The system of any of Aspects 1-3, wherein the distributor assembly is operationally configured to provide at least 10% greater flow per unit bundle area of the refrigerant through the second cavity than through the first cavity when the valve is in a fully open position.

[0015] Aspect 6. The system of any of Aspects 2-5, further comprising a first expansion conduit having an expansion valve, the first expansion conduit being in fluid flow communication with the cold end of the second set of tubes of a first tube bundle of the at least one tube bundle, and being in fluid flow communication with the central conduit of the first tube bundle.

[0016] Aspect 7. The system of any of Aspects 2-6, wherein a first tube bundle of the at least one tube bundle further includes a third set of tubes having a cold end and a warm end, the third set of tubes being in fluid flow communication with a second refrigerant conduit.

[0017] Aspect 8. The system of claim **7**, further comprising a second expansion conduit having an expansion valve, the second expansion conduit being in fluid flow communication with the cold end of the third set of tubes of a second tube bundle of the at least one tube bundle, and being in fluid flow communication with the central conduit of the second tube bundle.

[0018] Aspect 9. The system of any of Aspects 7 or 8, wherein the first refrigerant conduit is operationally configured to supply a vapor stream of the refrigerant to the warm end of the second set of tubes, the second refrigerant conduit is operationally configured to supply a liquid stream of the refrigerant to the warm end of the third set of tubes.

[0019] Aspect 10. The system any of Aspects 1-9, wherein the at least one tube bundle includes a hot tube bundle and a cold tube bundle, the hot tube bundle being located below the cold bundle.

[0020] Aspect 11. The system of any of Aspects 1-10, further comprising a refrigerant compression circuit operationally configured to withdraw the refrigerant from the shell space at a location below a hot tube bundle of the at least one tube bundle, compress and cool the refrigerant, and return the refrigerant to the warm end of the hot tube bundle, wherein the hot tube bundle is located below any other bundles of the at least one tube bundle.

[0021] Aspect 12. The system of Aspect 11, wherein the refrigerant compression circuit comprises a warm end conduit, a compressor assembly, and a high-pressure conduit, the compressor assembly comprising having a low-pressure end and a high-pressure end, at least one multi-stage compressor and at least one heat exchanger, the warm end conduit being in fluid flow communication with the shell space at a location below the hot tube bundle and being in fluid flow communication with the low-pressure end of the compressor assembly, the high-pressure conduit being in fluid flow communication with the high-pressure end of the compressor assembly and the warm end of the hot tube bundle.

[0022] Aspect 13. The system of any of Aspects 1-12, wherein the feed gas is natural gas.

[0023] Aspect 14. A method of cooling a feed gas stream flowing through at least one tube bundle located within a shell space of a heat exchanger against a refrigerant, each of the at least one tube bundle comprising at least one set of tubes helically wrapped around a central mandrel, the method comprising:

- **[0024]** (a) irrigating at each of the at least one tube bundle with the refrigerant by enabling the refrigerant to flow through a distributor assembly having a plurality of arms located above each of the at least one tube bundle;
- **[0025]** (b) allowing the refrigerant to flow directly from a central conduit to a first cavity of each of the plurality of arms, the first cavity including a plurality of apertures;
- **[0026]** (c) controlling flow of the refrigerant to a second cavity of at least one of the plurality of arms of the distributor assembly by operating a valve located on or upstream from a bypass conduit that provides fluid flow communication between the central conduit and the second cavity and providing a separating wall located between the first and second cavities to inhibit fluid flow communication between the first and second cavities, the second cavity including a plurality of apertures and being located at a greater radial distance from the central mandrel than the first cavity.

[0027] Aspect 15. The method of Aspect 14, further comprising:

- **[0028]** (d) selecting a location of each of the separating walls as a function of the first and second areas of the at least one tube bundle, the first area comprising a portion of the tube bundle extending from the central mandrel to the separating wall and the second area comprising a second portion of the tube bundle extending from the separating wall to an outer end of the second cavity.

[0029] Aspect 16. The method of Aspect 15, wherein step (d) comprises selecting the location of each of the separating walls so that the first and second areas are substantially equal.

[0030] Aspect 17. The method of any of Aspects 14-16, further comprising:

- **[0031]** (e) measuring a plurality of temperatures of a first tube bundle of the at least one tube bundle, each of the plurality temperatures being taken at different radial distance from the central mandrel;
- **[0032]** (f) setting the position of each valve located on each bypass conduit for the distributor assembly located above the first tube bundle as a function of the plurality of temperatures.

[0033] Aspect 18. The method of any of Aspects 14-17, further comprising:

- **[0034]** (g) withdrawing the refrigerant from a warm end of the shell space;
- **[0035]** (h) compressing and cooling the withdrawn refrigerant; and
- **[0036]** (i) reintroducing the compressed and cooled refrigerant into a warm end of one of the at least one tube bundle.

[0037] Aspect 19. The method of any of Aspects 14-18, wherein step (a) further comprises irrigating a first tube bundle of the at least one tube bundle with a first refrigerant stream withdrawn from a cold end of the first tube bundle and irrigating a second tube bundle of the at least one tube bundle with at least a portion of the first refrigerant stream.

[0038] Aspect 20. The method of Aspect 19, wherein step (a) further comprises irrigating the second tube with a second refrigerant stream withdrawn from a cold end of the second tube bundle.

BRIEF DESCRIPTION OF THE FIGURES

[0039] Other aspects, features, and advantages of the described embodiments will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements.

[0040] FIG. **1** shows a schematic of a mixed refrigerant coil-wound heat exchanger for liquefaction of natural gas in accordance with described embodiments;

[0041] FIG. **2** shows an elevation view of a conventional distributor arm design located at the top of the tube bundles of a coil wound heat exchanger;

[0042] FIG. **3** shows an elevation view of a distributor arm design located at the top of the tube bundles of a coil wound heat exchanger in accordance with described embodiments;

[0043] FIGS. **4-6** show plan views of a cross-sections of a cylindrical heat exchanger showing distributor arm designs in accordance with described embodiments;

[0044] FIG. **7** shows a plot of cooling curves showing feed tube-side (T-Hot) and shell-side (T-Cold) temperatures for an inner distributor section for an initial exemplary use scenario;

[0045] FIG. **8** shows a plot of cooling curves showing feed tube-side (T-Hot) and shell-side (T-Cold) temperatures for an outer distributor section for an initial exemplary use scenario;

[0046] FIG. **9** shows a plot of cooling curves showing feed tube-side (T-Hot) and shell-side (T-Cold) temperatures for an inner distributor section for a final exemplary use scenario; and

[0047] FIG. **10** shows a plot of cooling curves showing feed tube-side (T-Hot) and shell-side (T-Cold) temperatures for an inner distributor section for a final exemplary use scenario.

DETAILED DESCRIPTION

[0048] The ensuing detailed description provides preferred exemplary embodiments only, and is not intended to limit the scope, applicability, or configuration of the claimed invention. Rather, the ensuing detailed description of the exemplary embodiments will provide those skilled in the art with an enabling description for implementing the exemplary embodiments of the claimed invention. Various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the invention, as set forth in the appended claims.

[0049] The term "conduit," as used in the specification and claims, refers to one or more structures through which fluids can be transported between two or more components of a system. For example, conduits can include pipes, ducts, passageways, and combinations thereof that transport liquids, vapors, and/or gases.

[0050] The term "fluid flow communication," as used in the specification and claims, refers to the nature of connectivity between two or more components that enables liquids, vapors, and/or gases to be transported between the components in a contained fashion (i.e., without substantial leakage). Coupling two or more components such that they are in flow communication with each other can involve any suitable method known in the art, such as with the use of welds, flanged conduits, gaskets, and bolts. Two or more components may also be coupled together via other components of the system that may separate them.

[0051] The term "natural gas", as used in the specification and claims, means a hydrocarbon gas mixture consisting primarily of methane.

[0052] Directional terms may be used in the specification and claims to describe portions of the present invention (e.g., upper, lower, left, right, etc.). These directional terms are merely intended to assist in describing exemplary embodiments, and are not intended to limit the scope of the claimed invention. As used herein, the term "upstream" is intended to mean in a direction that is opposite the direction of flow of a fluid in a conduit from a point of reference. Similarly, the term "downstream" is intended to mean in a direction that is the same as the direction of flow of a fluid in a conduit from a point of reference.

[0053] Reference numerals that are introduced in the specification in association with a drawing Figure may be repeated in one or more subsequent Figures without additional description in the specification in order to provide context for other features.

[0054] In the claims, letters may be used to identify claimed method steps (e.g. (a), (b), and (c)). These letters are used to aid in referring to the method steps and are not intended to indicate the order in which claimed steps are performed, unless and only to the extent that such order is specifically recited in the claims.

[0055] Described embodiments provide a novel distributor assembly which enables adjustment of shell-side flow distribution to improve temperature distribution of a heat exchanger at any process conditions by adjustment of shell-side fluid flow rate at various radial locations in the coil wound heat exchanger. FIG. **1** shows a simplified schematic of a natural gas liquefaction system **100** employing a three bundle coil wound heat exchanger (CWHE) **102**. CWHE **102** employs a mixed refrigerant (MR) and includes three tube bundles: a cold bundle **104**, a middle bundle **106**, and a hot bundle **108**. Each tube bundle **104**, **106**, and **108** includes process tubes wrapped in a helical fashion in concentric layers around a central mandrel **146**. The tubes are connected to tube-sheets (not shown) located above and below each bundle **104**, **106**, **108**. Each bundle has a warm end, where fluid flows into the tubes, and a cold end, where fluid flows out of the tubes. Preferably, each tube bundle **104**, **106** and **108** occupies a continuous volume within the shell space. In other words, it is preferable that each of the tube bundles not be divided into radially-spaced sections. Applicants have discovered that such sections merely add complexity and cost to the CWHE and do not significantly improve temperature distribution.

[0056] A natural gas stream **116** enters at the bottom end (warm end) of the CWHE **102** via a warm natural gas conduit **115**. In some embodiments, the natural gas stream **116** will undergo optional pre-processing before entering CWHE **102**. The optional pre-processing system **118** is shown schematically in FIG. **1**. Examples of pre-processing include removing impurities such as water, acid gases and mercury, and cooling the natural gas stream against propane in a heat exchanger. The natural gas stream is cooled and liquefied as it flows through the tubes and exits CWHE **102** as liquefied natural gas (LNG) in a liquefied gas conduit **117**. The LNG might be stored in a LNG tank **122** and/or fed via LNG outlet **124** to other systems.

[0057] Two MR streams are also cooled by flowing through tube bundles. These streams are introduced by conduits **112** and **114**, which are described in greater detail herein. MR is withdrawing at the top of the middle bundle **106** and the cold bundle **104**, then expanded by flashing across an expansion valves **128** and **120**, respectively, to produce cold shell-side MR streams. Joule-Thomson (J-T) valve is an example of a suitable expansion valve. The cold shell-side MR streams are carried to the central mandrel **146** via conduits **130** and **126**, respectively, where the streams are use to provide the refrigeration duty to cool down and liquefy the natural gas flowing through the tube bundles **104**, **106**, **108**. In some embodiments, the cold shell-side MR stream flowing through conduit **130** has a temperature in the range of −60 to −120 degrees Celsius and cold shell-side MR stream flowing through conduit **126** has a temperature in the range of −120 to −150 degrees Celsius. Located at the top of each tube bundle is a corresponding distributor assembly, shown as distributors **110***a*, **110***b*, and **110***c*, that distributes the shell-side MR across the top of the tube bundle. As will be explained herein, in some embodiments the central mandrel **146** is considered part of the distributor assembly.

[0058] A warm, low pressure MR stream flow from the CWHE **102** is circulated through a refrigerant compression circuit before being returned to the CWHE. In this embodiment, the warm, low pressure MR stream preferably exits the CWHE **102** at a pressure less than 10 bar and, more preferably, about 5 bar. The temperature of the warm, low pressure MR stream is typically similar to the temperature of the natural gas stream **116** but will depend upon the cycle being used. For example, a temperature of about −35 degrees Celsius would be typical in a C3MR cycle, a temperature as low as −60 degrees Celsius is possible for a DMR cycle and ambient temperature is typical for an SMR cycle. The warm, low pressure MR flow **131** flows from the warm end of the shell space through a warm end conduit to a compressor assembly **133**, where the MR stream is compressed and cooled against ambient air to produce an MR stream that exits the compressor assembly to form high pressure refrigerant flow **137**. The high pressure refrigerant stream is typically at ambient temperature and a pressure of at least 30 bar and, more preferably, between 40 and 90 bar.

[0059] As shown in FIG. **1**, in this embodiment, the compressor assembly **133** includes a multi-stage compressor including two compressors **134** and **136**, two heat exchangers **138** and **142** and a suction drum **140**. In this embodiment, the compressor assembly **133** is powered by a motor **132**. In this embodiment, the heat exchangers **138** and **142** cool the MR stream against ambient air. It should be understood that the configuration of the compressor assembly **133** shown in FIG. **1** is exemplary. In other embodiments, a different number of compressors and/or heat exchangers could be provided.

[0060] The high pressure refrigerant flow **137** then enters phase separator **144** to produce mixed refrigerant vapor (MRV) stream via conduit **112**, and a mixed refrigerant liquid (MRL) stream via conduit **114**. The shell-side MR is separated into vapor and liquid phases in the phase separator to improve liquid distribution. Although the phase separator **144** is shown in FIG. **1** as being external to the CWHE **102**, it might be implemented as a single unit with CWHE **102**.

[0061] It is important that the shell-side refrigerants and tube side flow is evenly distributed over all the layers of tubes in the tube bundles. Radial mal-distribution of the shell-side fluid or the tube side flow may lead to uneven temperature profiles across the radius of the heat exchanger. This is especially applicable to floating natural gas liquefaction (FLNG) facilities where sea conditions may lead to vessel motion which may, in turn, cause non-optimal distribution of the shell-side fluid. This could result in a range of temperatures for the fluids exiting the tubes on the cold end of the bundles. The uneven heat transfer in turn causes a reduction in the effectiveness of the heat exchanger and the efficiency of the liquefaction process. Thus, in the design of a CWHE, substantial effort is made in design and manufacturing to ensure proper distribution of fluids on both the tube side and shell side. Described embodiments ensure even distribution regardless of process conditions and allow for adjusting radial flow distribution even under high vessel motion conditions.

[0062] FIG. **2** shows an elevation view diagram of a conventional shell-side distribution system **210** with multiple distributor arms within the shell of the CWHE **102** of FIG. **1**. FIG. **2** shows a distributor body **154** with two distributor arms **155** and **157**. A distributor irrigates MR across the top of each tube bundle of the CWHE **102**, as represented by the arrows **156** and **158**. The shell-side liquid refrigerant **148** flows through a central conduit **245** in the central mandrel **246** and is split roughly equally among the distributor arms, as represented by arrows **150** and **152** into the distributor cavity **153**. These streams enter into the distributor arms, flow through apertures (not shown) formed thereon, and onto the tube bundle below the distributor body **154**. A plate **247**, which spans the central mandrel **246**, prevents shell-side MR from continuing to flow downwardly past the distributer arms **155**, **157**.

[0063] In this embodiment, the wall that forms that central mandrel **246** and defines the central conduit **245** are one in the same. As described above, the primary function of the central mandrel **246** is to provide a structure around which the tube bundles are wound. The primary function of the central conduit **245** is to allow the shell-side MR stream to flow into the distributer arms. Accordingly, in alternate embodiments the central mandrel **246** and central conduit **245** could be separate structures. For example, the central conduit **245** could be a pipe located within the central mandrel **246**.

[0064] When in operation, at least a portion of the central conduit **245** preferably filled with shell-side MR. This applies to both the prior art distributor system **210** shown in FIG. **2**, as well as embodiments of the distributor of the present invention. An exemplary fill level **249** is shown in FIG. **2**.

[0065] FIG. **3** shows an exemplary embodiment of a distributor assembly **310**. In this embodiment, the distributor arms **255** and **257** are each divided into multiple sections (or cavities). These cavities are shown in FIG. **3** as outer distributor cavities **184** and **186**, and inner distributor cavities **183** and **185**. The outer distributor cavities **184** and **186** are located at a greater radial distance from the central conduit **345** than the inner distributor cavities **183** and **185**. Although the distributor arms are divided into two sections (e.g., inner and outer sections) in this embodiment, any number of sections might be employed in alternative embodiments.

[0066] In this embodiment, the distributor arms are divided into separate sections by one or more distributor cavity partitions (or walls) **192** and **196**. In this embodiment, the distributor cavity partitions **192** and **196** (also referred to as separating walls) prevent any shell-side MR from flowing between cavities. Although preventing any flow is preferred, the walls could alternatively merely inhibit shell-side MR from flowing between cavities. As will be explained in greater detail herein, this configuration enables the greater control over the flow of shell-side MR at different radially-spaced portions of the tube bundles. In the embodiment shown in FIG. **3**, an inner portion of the tube bundle is irrigated by the inner distributor cavities **183** and **185** of the distributor arm and an outer portion of the tube bundle is irrigated by the outer distributor cavities **184** and **186** of the distributor arms.

[0067] The shell-side liquid refrigerant flow **248** enters through the central conduit **345** and is distributed to each cavity of the distributor arms **255** and **257**. Shell-side liquid refrigerant flows **176** and **182** are shown to flow into the outer distributor cavities **184** and **186**, respectively, via bypass conduits **174** and **180** and bypass valves **172** and **178**. The irrigation flow of MR downwardly from the outer distributor cavities **184** and **186** is represented by flows **188** and **190**, respectively. Distributor arm refrigerant flows **250** and **252** enter inner distributor cavities **183** and **185**, respectively. Accordingly, the inner distributor cavities **183** and **185** are in direct fluid flow communication with the central conduit **345**, meaning that shell-side liquid refrigerant flows directly and freely from the central mandrel **346** into the inner distributor cavities **183** and **185**. In contrast, shell-side MR is supplied to the outer distributor cavities **184** and **186** only through the bypass conduits **174** and **180**. The irrigation flow of MR downwardly from the inner distributor cavities **183** and **185** is represented by flows **156** and **158** respectively.

[0068] Bypass valves **172** and **178** are used to adjust the flow split between outer distributor cavities **184** and **186** and inner distributor cavities **183** and **185**. It is not necessary that all valves are adjusted in unison, rather, individual valves might be adjusted independently to different ratios, or it is possible that only one valve might be adjusted to obtain the shell-side flow distribution required. This makes the system easier to operate, since all the valves are not required to be adjusted.

[0069] In an alternate arrangement (not shown), shell-side liquid refrigerant flow **248** might be divided into two streams, one to feed inner distributor cavities **183** and **185** and the other to feed outer distributor cavities **184** and **186**. One valve might be used to control the flow split between the two sections. In this scenario, the cavity fed through the valve will preferably have more and/or larger apertures so that the outer cavities will have higher flow in the non-adjusted condition, such that it is possible to partly close the valve opening and make the distribution even. In other words, the total area of the apertures per unit bundle area in each outer cavity of an arm is larger than the total area of the apertures per unit bundle area in the inner cavity of that arm. Preferably, the distributor assembly **310** is operationally configured so that at least 10% more (more preferably, at least 20% more) shell-side MR flows through the outer distributor cavity **184** per unit bundle area than flows through the inner distributor cavity **183** when the bypass valve **172** is in a fully open position. Each stream might then be divided equally to evenly flow into the individual distributor arms (e.g., **255** and **257**). The split is adjusted accordingly to optimize flow distribution. Although the descriptions above show two sections in the distributor arms, multiple such sections may be employed by inserting additional distributor cavity partitions (e.g., **192** and **196**) and creating additional cavities. Each cavity might have independently controlled MR flows (e.g., separate valves and conduits). Additionally, several variations are possible wherein the flow between the sections in the distributor arms may be split in different ways. One such arrangement is where additional set of distributor arms exist that only occupy a portion of the radius of the exchanger. Other arrangements may differ in the piping configuration, for example the valves might regulate flow to the inner distributor cavities **183** and **185** rather than the outer distributor cavities **184** and **186**, the valves might regulate flow to both the inner distributor cavities **183** and **185** and the outer distributor cavities **184** and **186**, and/r one bypass conduit could extend from the central conduit into a single valve and the output flow from the valve could be distributed to each of the outer distributor cavities **184**,**186**.

[0070] Optionally, in order to more accurately control the operation of the bypass valves **172** and **178**, temperatures sensors, such as thermocouples for example, could be positioned on the tubes of a tube bundle at different radial distances from the central mandrel **346**. The desired position of each of the bypass valves **172** and **178** could be determined and, if necessary, adjusted based on temperature measurements from the sensors. Such adjustment could be performed manually (e.g., by having a technician adjust each of the bypass valves **172** and **178** based on observed temperatures) or using a controller programmed to adjust the position of each of the bypass valves **172** and **178** based on data received from the temperatures sensors. Accordingly, the position of the bypass valves **172**, **178** is set as a function of the temperature readings of the temperatures sensors.

[0071] FIGS. **4** through **6** show plan views of cross sections of the cylindrical heat exchanger employing differing layouts of the distributor cavities and distributor arms. For example, in FIG. **4**, the four distributor arms, shown as arms **1-4**, of distributor system **410** are disposed around central mandrel **446**. As shown, each arm has an inner distributor cavity and an outer distributor cavity. For example, arm **1** includes inner distributor cavity **162***a* and outer distributor cavity **160***a*, arm **2** includes inner distributor cavity **164***b* and outer distributor cavity **166***b*, arm **3** includes inner distributor cavity **162***b* and outer distributor cavity **160***b*, and arm **4** includes inner distributor cavity **164***a* and outer distributor cavity **166***a*. Each distributor cavity corresponds to one of the inner distributor cavities **183** and **185** or outer distributor cavities **184** and **186** as shown in FIG. **3**.

[0072] Various distributor cavity shapes could be employed. For example, FIG. **4** shows the various distributor cavities are square or rectangular in shape. Alternatively, FIG. **5** shows distributor arms **11**, **12**, **13**, and **14** having distributor cavities (**260***a*, **260***b*, **262***a*, **262***b*, **2641**, **264***b*, **266***a*, **266***b*) are arc or wedge shaped. FIG. **6** shows a distributor system **610** with distributor arms **21**, **22**, **23**, and **24** having distributor cavities of varying dimensions of squares and rectangles, with larger distributor cavities irrigating the outer portion of the tube bundles (e.g., **360***a*, **360***b*, **366***a* and **366***b*) and smaller distributor cavities irrigating the inner portion of the tube bundles (e.g., **362***a*, **362***b*, **364***a* and **364***b*). In the exemplary distributor arm embodiments shown in FIGS. **4-6**, each distributor arm has a corresponding distributor arm (as indicated by the a and b reference numeral designators on the outlets) disposed 180 degrees offset around central mandrel **146**, **246**, **346**. This enables the heat exchanger to have well balanced distribution of MR radially within the heat exchanger regardless of, for example, a tilt or pitch of the heat exchanger, for example on a floating LNG system.

[0073] Referring again to FIG. **5**, optionally, the location of the separating walls **492***a*, **492***b*, **492***c*, **492***d*, is chosen as a function of the area A**1** of the tube bundle extending from the central mandrel **546** to an outer edge of the inner distributor cavities **262***a*, **262***b*, **264***a*, **264***b* (represented by line **451** in FIG. **5**) and the area A**2** of the tube bundle extending from the separating walls **492***a*, **492***b*, **492***c*, **492***d* to an outer edge of the outer distributor cavities **260***a*, **260***b*, **266***a*, **266***b* (represented by line **449** in FIG. **5**). In some embodiments, the location of the separating walls **492***a*, **492***b*, **492***c*, **492***d* is chosen so that the first and second areas A**1**, A**2** are substantially equal. In this context, substantially equal means that the difference between areas A**1**, A**2** is no more than 5 percent of the total area.

[0074] In addition, it is preferable that the distributor assembly **510** be operationally configured to provide a greater "flow per unit bundle area" of shell-side MR through the outer distributor cavity of each arm than through the inner distributor cavity when the valve that controls shell-side MR flow to the outer distributor cavity is fully open. For purposes of this application, "flow per unit bundle area" means the total area of apertures (not shown) located in the distributor cavity in question divided by the area A**1** of the tube bundle located in the radial space occupied by that cavity. For example, the flow per unit bundle area of outer distributor cavity **260***a* would be the total area of all apertures located in outer distributor cavity **260***a* divided by area A**2**. As noted above, one way to accomplish this operational condition is to provide more apertures and/or larger apertures in the outer distributor cavities **260***a*, **260***b*, **266***a*, **266***b* than in the inner distributor cavities **262***a*, **262***b*, **264***a*, **264***b*.

[0075] Although the embodiments are described herein as being employed in liquefaction of natural gas, the described embodiments are applicable to other processes where a stream is cooled or liquefied. Further, although described herein as adjusting radial distribution of the MR, similar concepts might be used to adjust circumferential distribution of the MR. The described embodiments might be employed in any cylindrical heat exchanger where liquid distribution is required and are not restricted to coil wound heat exchangers.

EXAMPLE

[0076] In an exemplary operation, the hot bundle of a coil wound heat exchanger (e.g., hot bundle **108**) employing a C3MR liquefaction cycle comprises three tube circuits; one each for the feed, mixed refrigerant liquid (MRL) and mixed refrigerant vapor (MRV) streams. Initially, inner distributor cavities **183** and **185** and outer distributor cavities **184** and **186** of the distributor arms receive equal amounts of shell-side MR and irrigate the inner and outer portions of the tube bundles equally. In other words, flows **250** and **252** are equal to flows **176** and **182**. It is assumed for this example that the inner distributor outlets have the same surface area as the outer distributor outlets. It is also assumed that the tube side MR is distributed in a ratio of 51:49. This scenario represents an "Initial" scenario described in Table 1 below.

[0077] FIG. **7** shows the cooling curves for the hot tube bundle **902** (e.g., **108**) and the cold tube bundle **904** (e.g., **102**) for inner distributor cavities **183** and **185**. FIG. **8** shows the cooling curves for the hot tube bundle **1002** (e.g., **108**) and the cold tube bundle **1004** (e.g., **102**) for outer distributor cavities **184** and **186**. The temperature of the feed tube circuit at the cold end of the hot bundle is colder on the outside of the bundle as compared to the inside. These cooling curves exhibit temperature "pinching" occurring at the warm end (FIG. **9**) and cold end (FIG. **8**) of the exchangers which results in a loss of effective overall surface area of about 2% compared with optimal distribution. To mitigate this, valves **120**, **128**, **172** and **178** can be adjusted to allow reduced relative flow of the shell-side MR to the outer sections as compared to the inner sections and match the tube side distribution. This scenario represents the "Final" column in Table 1 below. Streams **176** and **182** now have lower flow than streams **250** and **252**. FIG. **9** shows the optimized cooling curves for the hot tube bundle **1102** (e.g., **108**) and the cold tube bundle **1104** (e.g., **102**) for inner distributor cavities **183** and **185**. FIG. **10** shows the optimized cooling curves for the hot tube bundle **1202** (e.g., **108**) and the cold tube bundle **1204** (e.g., **102**) for outer distributor cavities **184** and **186**.

[0078] FIGS. **9** and **10** indicate a more optimal heat transfer across both sections. This is further confirmed by the calculated effective area value, shown in Table 1 below, which improved from 0.98 to 0.9995, where a value of 1.0 would result from a scenario in which both the tube side and shell side flow are distributed perfectly evenly.

[0079] Table 1 shows relative flowrates and area between the inner distributor cavities **183** and **185** and the outer distributor cavities **184** and **186** in the example operating case described above:

TABLE 1

	Initial	Final
Relative Tube side Flow	51:49	51:49
Relative Shell side Flow	50:50	51:49
Relative Area	50:50	50:50
Effective Overall Area	0.9809	0.9995

[0080] Thus, described embodiments are less complex than previously known systems. Further, described embodiments provide a method for optimizing the heat exchanger temperature profile by only controlling the shell-side flow rate, without also controlling the tube-side flow rate. Additionally, described embodiments allow adjustment of the shell-side radial flow distribution for only a single distributor arm. Unlike previously known systems, described embodiments can be applied to existing heat exchangers by replacing just the distributor arms without having to modify the tube bundles or overall heat exchanger.

[0081] While the principles of the claimed invention have been described above in connection with exemplary embodiments, it is to be clearly understood that this description is made only by way of example and not as a limitation of the scope of the claimed invention.

1. A system for indirect heat exchange between a feed gas and a refrigerant, the system comprising:

a feed gas conduit in flow communication with a supply of the feed gas;

a shell defining a shell space;

at least one tube bundle located in the shell space, each of the at least one tube bundle comprising a first set of tubes in fluid flow communication with the feed gas conduit, a central conduit, and a distributor assembly, the first set of tubes having a cold end and a warm end and being helically wrapped around a central mandrel, the distributor assembly having a plurality of arms located above the first set of tubes, each of the plurality of arms having a first cavity including a plurality of apertures, the first cavity being in direct fluid flow communication with the central conduit, the central conduit being in fluid flow communication with a supply of the refrigerant;

wherein at least one of the plurality of arms further comprises a second cavity including a plurality of apertures and a separating wall located between the first and second cavities to inhibit fluid flow communication between the first and second cavities, the second cavity being in fluid flow communication with the central conduit only through a bypass conduit and a valve, the second cavity being located at a greater radial distance from the central mandrel than the first cavity.

2. The system of claim **1**, wherein the at least one tube bundle further comprises a second set of tubes having a cold end and a warm end, the second set of tubes being located below the plurality of arms, helically wrapped around the central mandrel, and in fluid flow communication with a first refrigerant conduit, the second set of tubes comprising the supply of the refrigerant to the central conduit.

3. The system of claim **1**, wherein the central conduit comprises the central mandrel and a plate located within the central mandrel comprises a lower end of the central conduit.

4. The system of claim **1**, wherein the first cavity has a first flow per unit bundle area and the second cavity has a second flow per unit bundle area and the second flow per unit bundle area is greater than the first flow per unit bundle area.

5. The system of claim **1**, wherein the distributor assembly is operationally configured to provide at least 10% greater flow per unit bundle area of the refrigerant through the second cavity than through the first cavity when the valve is in a fully open position.

6. The system of claim **2**, further comprising a first expansion conduit having an expansion valve, the first expansion conduit being in fluid flow communication with the cold end of the second set of tubes of a first tube bundle of the at least one tube bundle, and being in fluid flow communication with the central conduit of the first tube bundle.

7. The system of claim **2**, wherein a first tube bundle of the at least one tube bundle further includes a third set of tubes having a cold end and a warm end, the third set of tubes being in fluid flow communication with a second refrigerant conduit.

8. The system of claim **7**, further comprising a second expansion conduit having an expansion valve, the second expansion conduit being in fluid flow communication with the cold end of the third set of tubes of a second tube bundle of the at least one tube bundle, and being in fluid flow communication with the central conduit of the second tube bundle.

9. The system of claim **7**, wherein the first refrigerant conduit is operationally configured to supply a vapor stream of the refrigerant to the warm end of the second set of tubes, the second refrigerant conduit is operationally configured to supply a liquid stream of the refrigerant to the warm end of the third set of tubes.

10. The system of claim **1**, wherein the at least one tube bundle includes a hot tube bundle and a cold tube bundle, the hot tube bundle being located below the cold bundle.

11. The system of claim **1**, further comprising a refrigerant compression circuit operationally configured to withdraw the refrigerant from the shell space at a location below a hot tube bundle of the at least one tube bundle, compress and cool the refrigerant, and return the refrigerant to the warm end of the hot tube bundle, wherein the hot tube bundle is located below any other bundles of the at least one tube bundle.

12. The system of claim **11**, wherein the refrigerant compression circuit comprises a warm end conduit, a compressor assembly, and a high-pressure conduit, the compressor assembly comprising having a low-pressure end and a high-pressure end, at least one multi-stage compressor and at least one heat exchanger, the warm end conduit being in fluid flow communication with the shell space at a location below the hot tube bundle and being in fluid flow communication with the low-pressure end of the compressor assembly, the high-pressure conduit being in fluid flow communication with the high-pressure end of the compressor assembly and the warm end of the hot tube bundle.

13. The system of claim **1**, wherein the feed gas is natural gas.

14. A method of cooling a feed gas stream flowing through at least one tube bundle located within a shell space of a heat exchanger against a refrigerant, each of the at least one tube bundle comprising at least one set of tubes helically wrapped around a central mandrel, the method comprising:

(a) irrigating at each of the at least one tube bundle with the refrigerant by enabling the refrigerant to flow through a distributor assembly having a plurality of arms located above each of the at least one tube bundle;

(b) allowing the refrigerant to flow directly from a central conduit to a first cavity of each of the plurality of arms, the first cavity including a plurality of apertures;

(c) controlling flow of the refrigerant to a second cavity of at least one of the plurality of arms of the distributor assembly by operating a valve located on or upstream from a bypass conduit that provides fluid flow communication between the central conduit and the second cavity and providing a separating wall located between the first and second cavities to inhibit fluid flow communication between the first and second cavities, the second cavity including a plurality of apertures and being located at a greater radial distance from the central mandrel than the first cavity.

15. The method of claim **14**, further comprising:

(d) selecting a location of each of the separating walls as a function of the first and second areas of the at least one tube bundle, the first area comprising a portion of the tube bundle extending from the central mandrel to the separating wall and the second area comprising a second portion of the tube bundle extending from the separating wall to an outer end of the second cavity.

16. The method of claim **15**, wherein step (d) comprises selecting the location of each of the separating walls so that the first and second areas are substantially equal.

17. The method of claim **14**, further comprising:

(e) measuring a plurality of temperatures of a first tube bundle of the at least one tube bundle, each of the plurality temperatures being taken at different radial distance from the central mandrel;

(f) setting the position of each valve located on each bypass conduit for the distributor assembly located above the first tube bundle as a function of the plurality of temperatures.

18. The method of claim **14**, further comprising:

(g) withdrawing the refrigerant from a warm end of the shell space;

(h) compressing and cooling the withdrawn refrigerant; and

(i) reintroducing the compressed and cooled refrigerant into a warm end of one of the at least one tube bundle.

19. The method of claim **14**, wherein step (a) further comprises irrigating a first tube bundle of the at least one tube bundle with a first refrigerant stream withdrawn from a cold end of the first tube bundle and irrigating a second tube bundle of the at least one tube bundle with at least a portion of the first refrigerant stream.

20. The method of claim **19**, wherein step (a) further comprises irrigating the second tube with a second refrigerant stream withdrawn from a cold end of the second tube bundle.

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