US 20180180363A1

(19) United States

(12) Patent Application Publication

Apte et al.

(10) Pub. No.: US 2018/0180363 A1

(43) Pub. Date: Jun. 28, 2018

(54) **MODULAR SHELL-AND-TUBE HEAT EXCHANGER APPARATUSES AND MOLDS AND METHODS FOR FORMING SUCH APPARATUSES**

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(21) Appl. No.: **15/392,523**

(22) Filed: **Dec. 28, 2016**

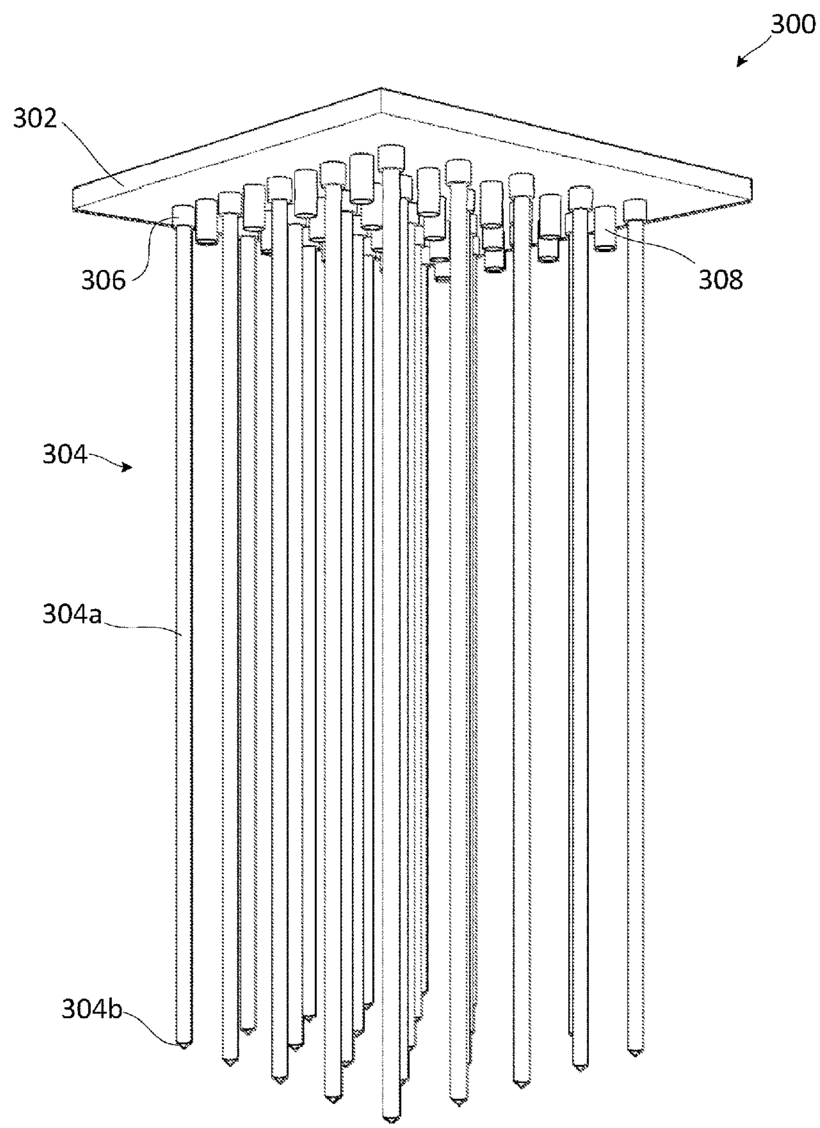
Publication Classification

(51) **Int. Cl.**
F28F 9/18 (2006.01)
F28F 9/04 (2006.01)
F28F 9/013 (2006.01)

(52) **U.S. Cl.**
CPC ***F28F 9/182*** (2013.01); *F28D 7/103* (2013.01); ***F28F 9/0131*** (2013.01); ***F28F 9/04*** (2013.01)

(57) **ABSTRACT**

Modular tubing apparatuses for use in a shell-and-tube heat exchanger are described. Multiple apparatuses may be connected in series to form a high density, small tube diameter, long length tube apparatus assembly. Casting molds for forming modular tubing apparatuses are likewise described, including methods for casting such apparatuses.



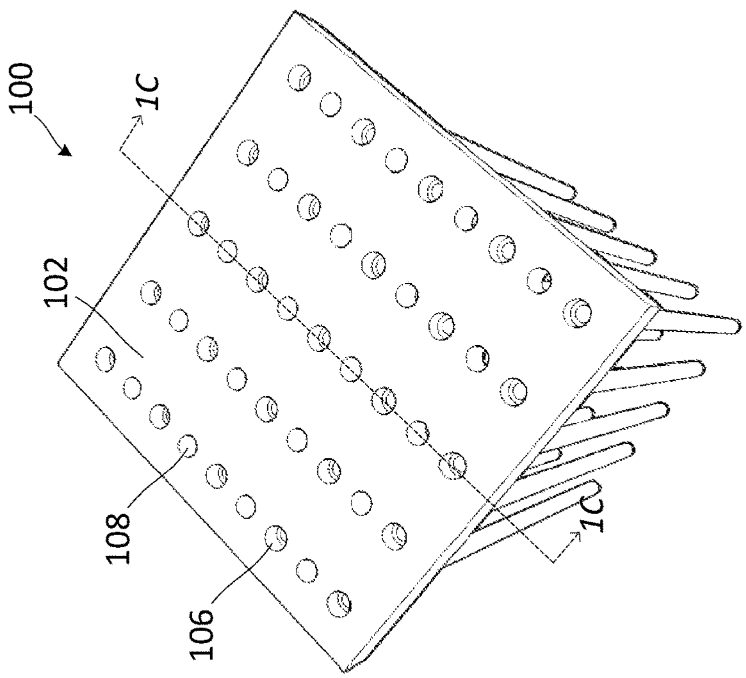


FIG. 1B

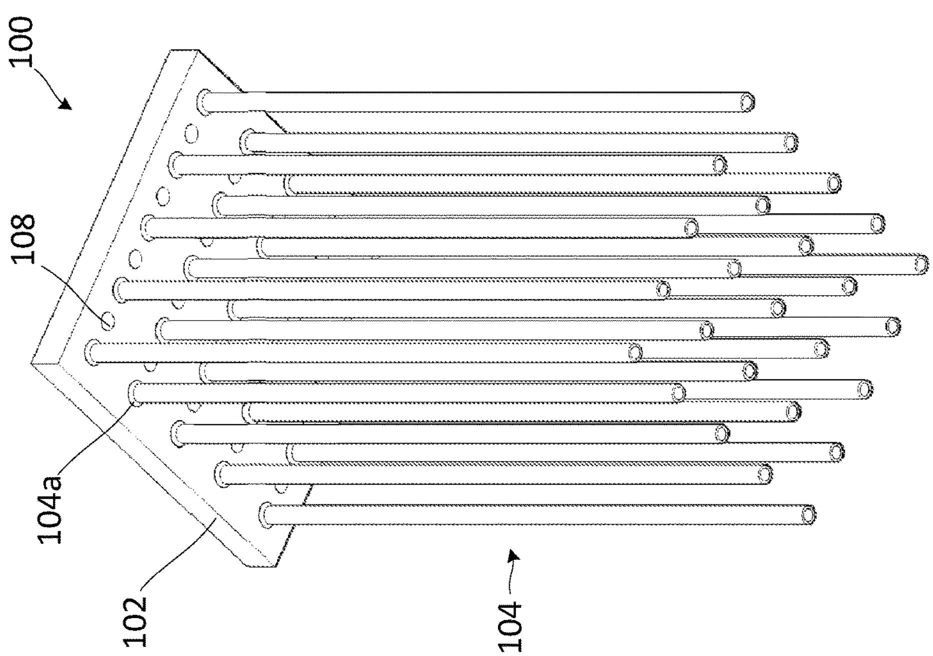
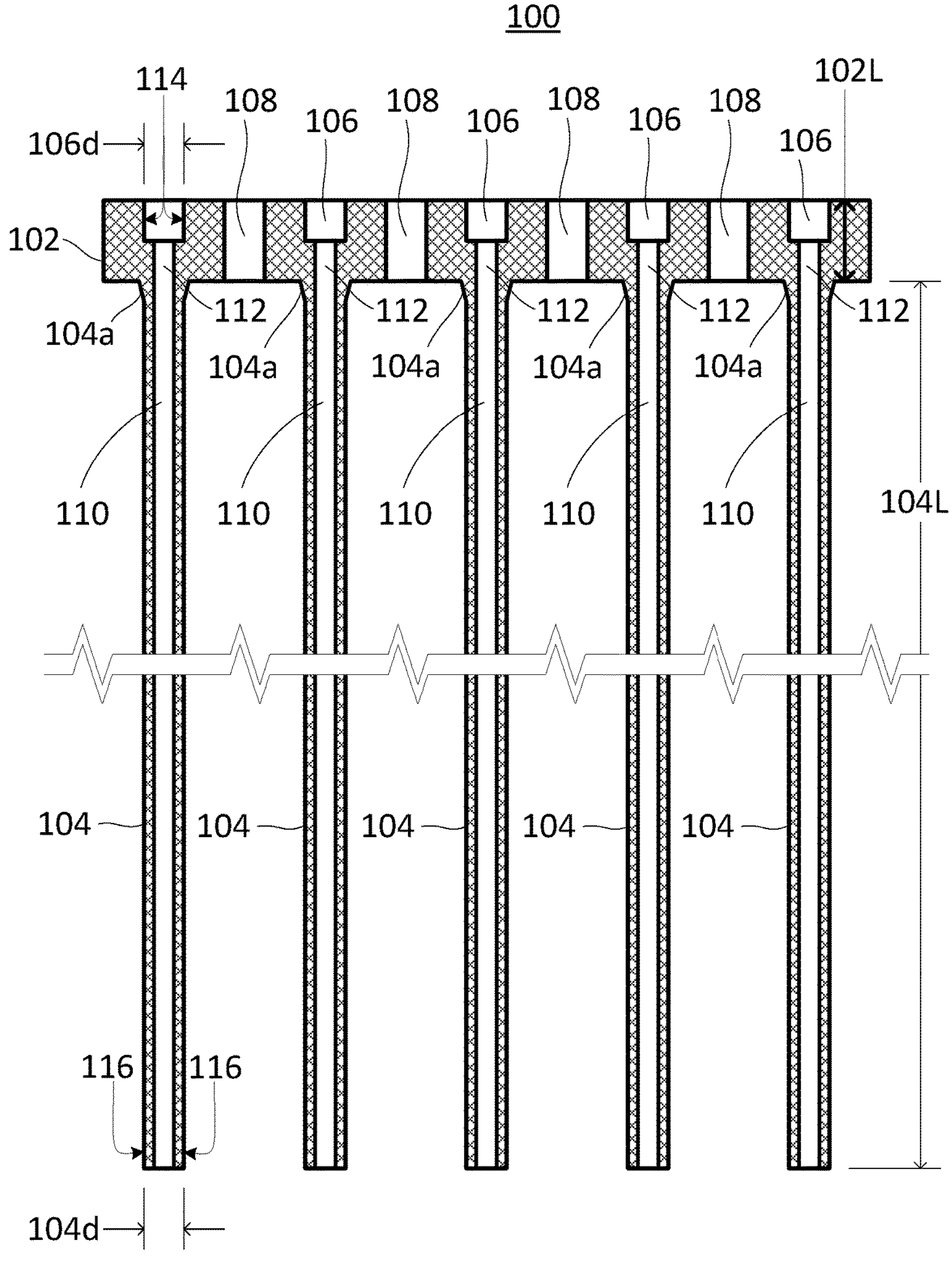


FIG. 1A


100
114
108
106
108
106
108
106
108
106
102L
106d
102
112
104a
112
104a
112
104a
112
104a
112
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110
110
104L
104
104
104
104
104
116
116
104d

FIG. 1C

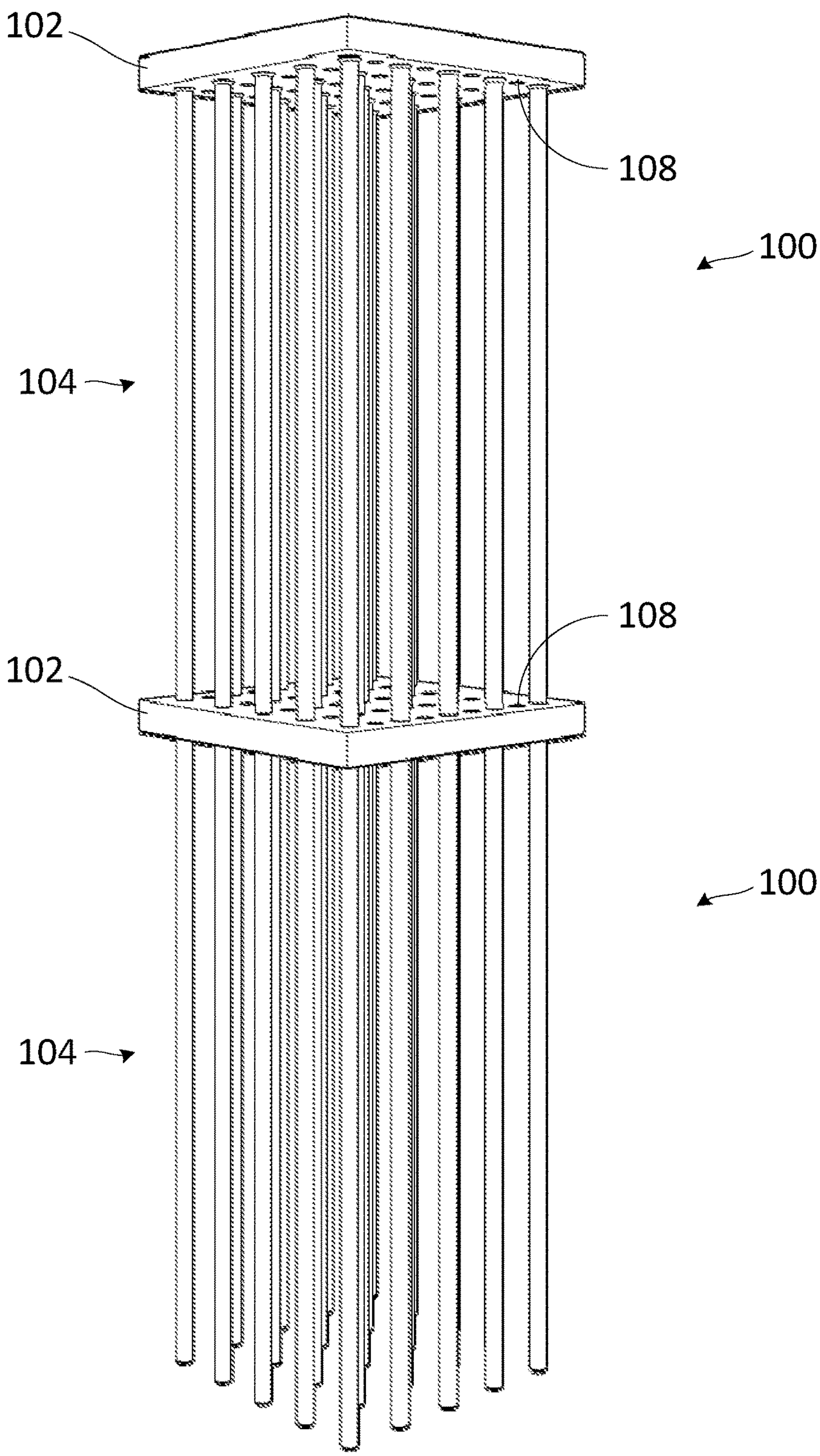

FIG. 2A

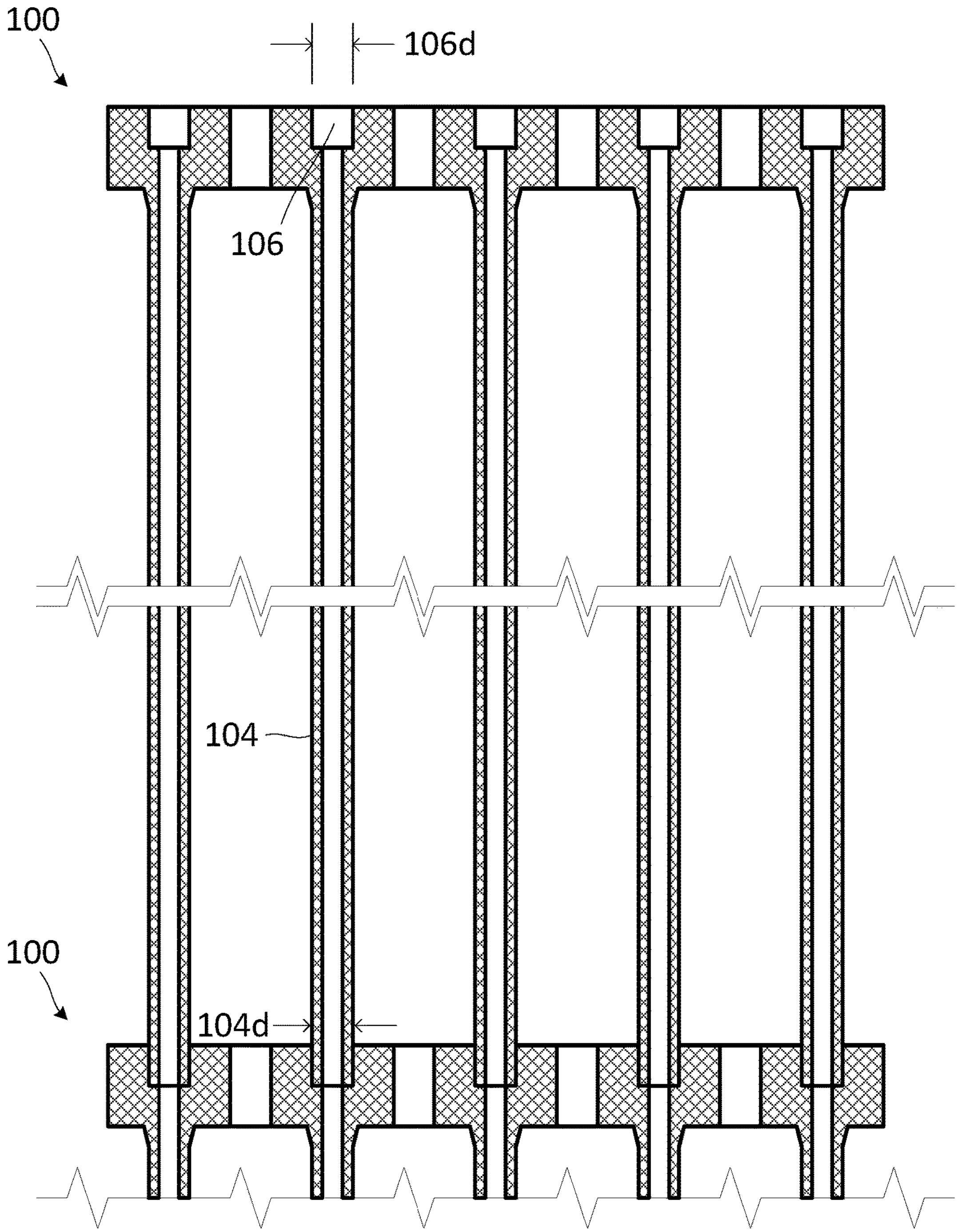

FIG. 2B

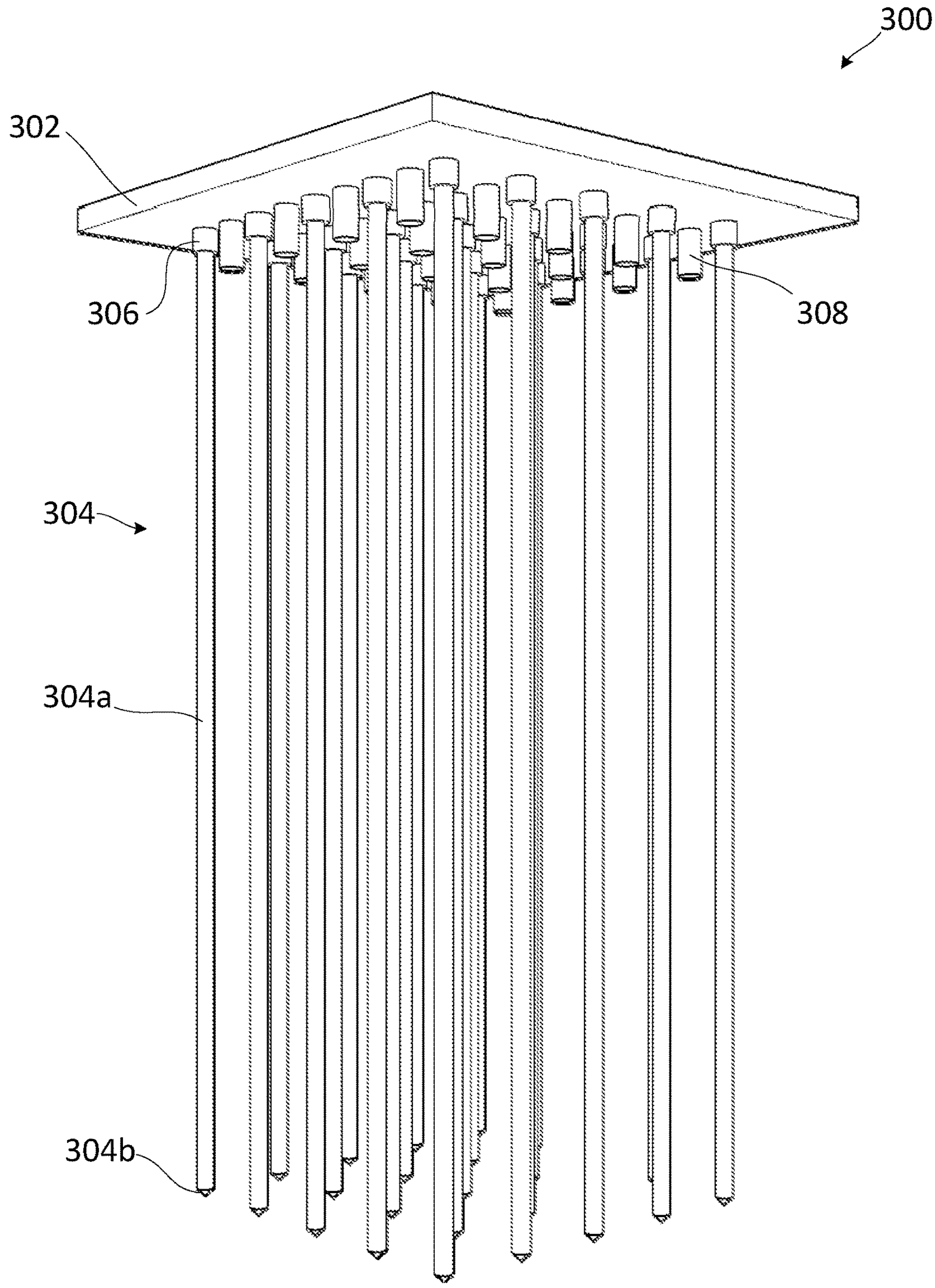

FIG. 3

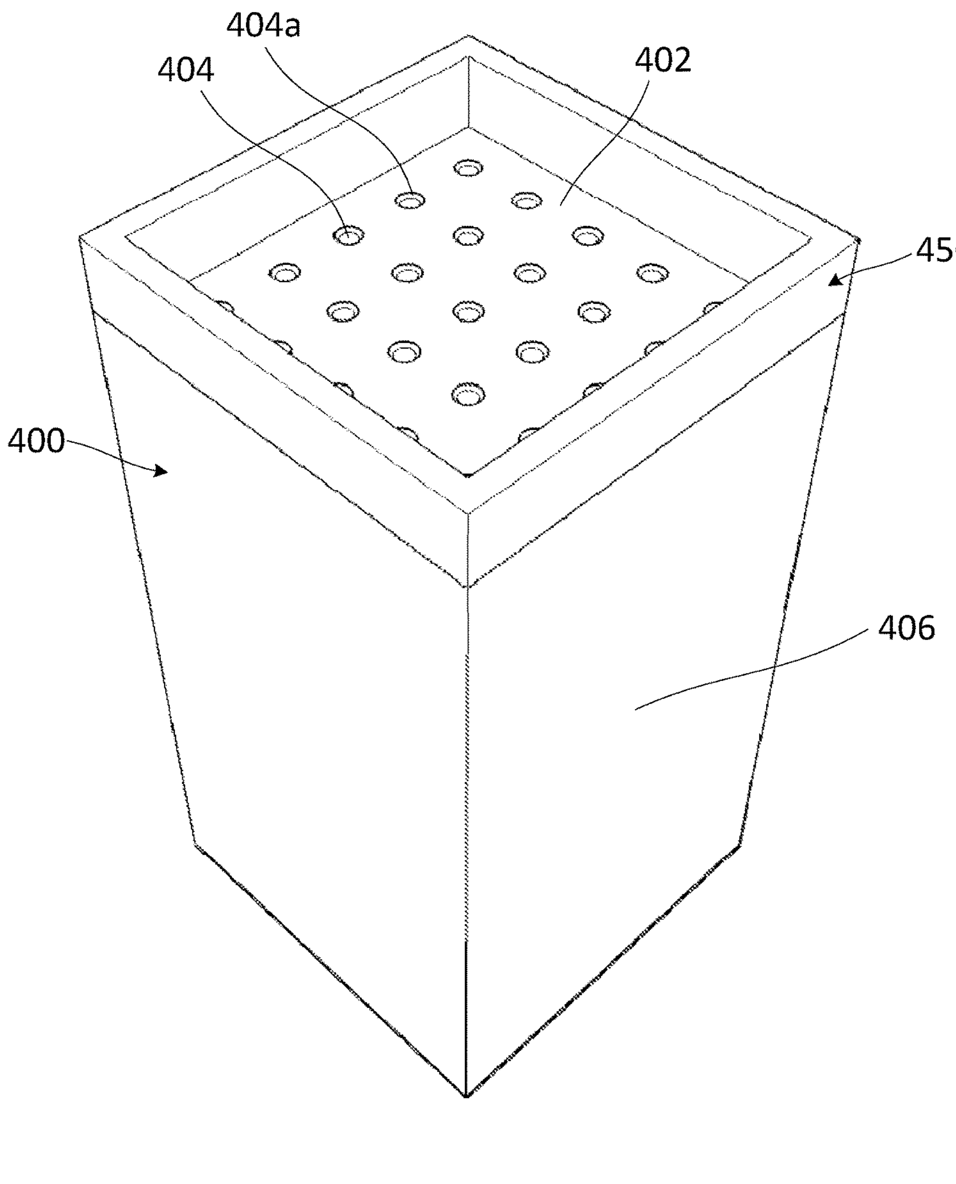

FIG. 4

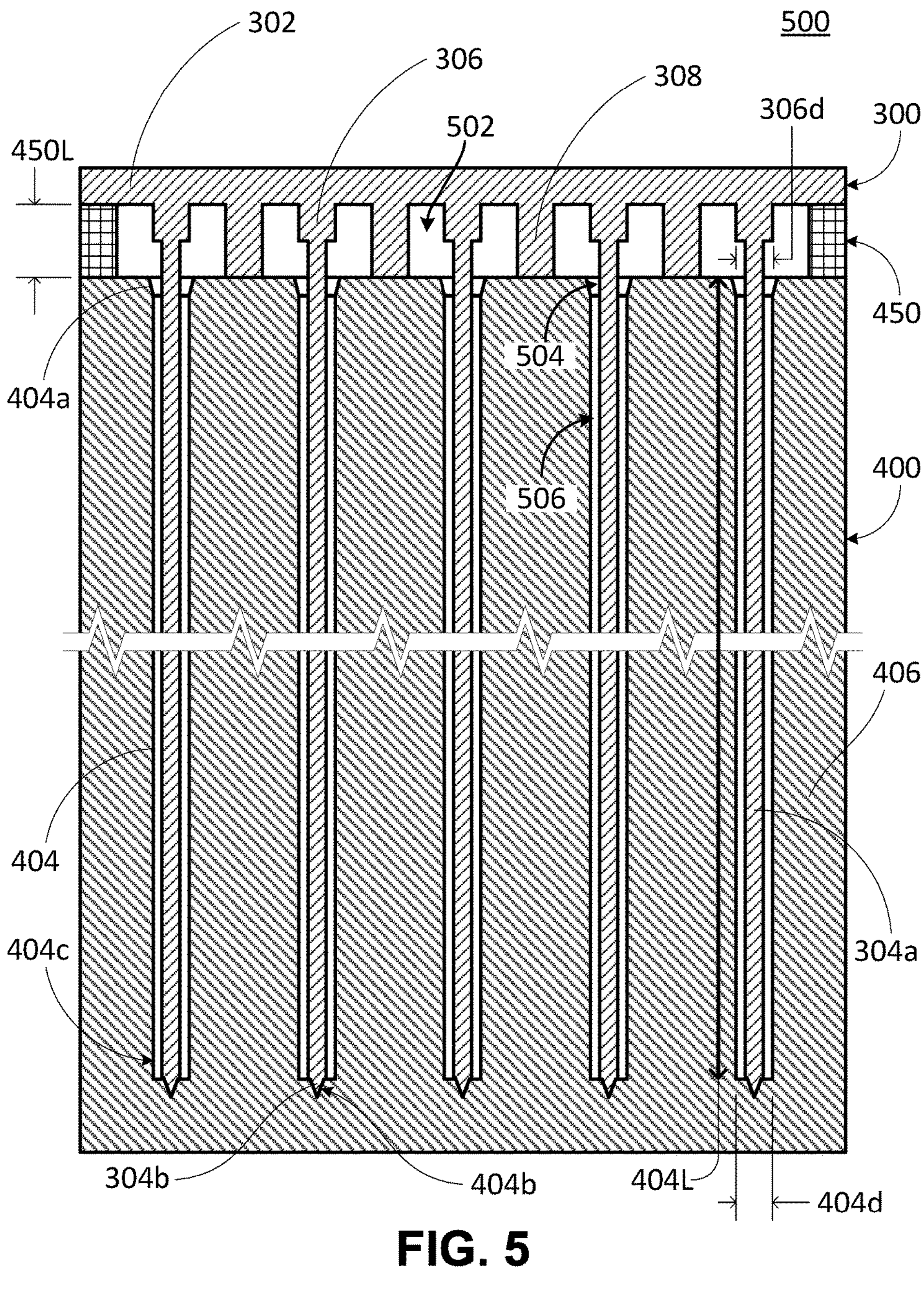
302
500
306
308
502
306d
300
450L
450
504
404a
506
400
406
404
304a
404c
304b
404b
404L
404d

FIG. 5

MODULAR SHELL-AND-TUBE HEAT EXCHANGER APPARATUSES AND MOLDS AND METHODS FOR FORMING SUCH APPARATUSES

BACKGROUND

[0001] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

[0002] High performance heat exchangers that achieve very low approach temperatures (for example, effectiveness greater than 99%) and very low pressure drops (for example, less than 5% or 1% calculated as (change in pressure)/(inlet pressure) across the heat exchanger) generally require very small diameter (for example, less than 10 mm) fluid passages with long lengths (for example, 0.5 m or 1 m or greater). Forming a large quantity of fluid passages (for example, greater than 100,000) with the above noted dimensions and then assembling enough of them in parallel to achieve large heat duties, such as might be used on a grid-scale energy generation or storage system, represents a significant manufacturing challenge.

[0003] Conventional methods of constructing shell-and-tube heat exchangers with long length, small diameter tubes have significant limitations. To form the tubes, mandrel rod drawing or floating plug drawing is typically used, but there are limitation such as manufacturing throughput, the need for intermediate tube diameters for drawing over the mandrel or plug, and additional secondary operations, such as mandrel reeling (removal). Finally, a dense array of individual tubes must then be coupled to an input plenum and output plenum in a time consuming and sometimes low-reliability assembly process.

SUMMARY

[0004] Disclosed herein are modular tube apparatuses for shell-and-tube heat exchangers, and molds and methods for forming the apparatuses.

[0005] Example apparatuses may include a connecting plate, a plurality of tubes extending from a bottom surface of the connecting plate, wherein each tube of the plurality of tubes comprises a distal open end and a hollow portion extending from the distal open end to the connecting plate, a plurality of receiving cups, wherein each receiving cup of the plurality of receiving cups is recessed into a top surface of the connecting plate to a depth partially through the connecting plate and disposed opposite a respective tube of the plurality of tubes, and wherein each receiving cup of the plurality of receiving cups defines an internal contour that conforms to an outer contour of the distal open end of the respective tube of the plurality of tubes, a first plurality of fluid paths inside the connecting plate, wherein each fluid path of the first plurality of fluid paths extends from each receiving cup of the plurality of receiving cups to the hollow portion of each respective tube of the plurality of tubes, and a second plurality of fluid paths through the connecting plate, wherein each fluid path of the second plurality of fluid paths extends from the top surface of the connecting plate to the bottom surface of the connecting plate.

[0006] Example mold assemblies may include a bottom mold portion that may include a bottom block comprising a top surface, and a plurality of cavities in the bottom block extending downwardly from the top surface to a first depth. Example mold assemblies may further include a top mold portion that may include a top plate positioned opposite and at a first distance from the top surface of the bottom block, a first plurality of protrusions extending downwardly from the top plate to a length less than the first distance, wherein each protrusion of the first plurality of protrusions is disposed opposite a respective cavity of the plurality of cavities, and wherein each protrusion of the first plurality of protrusions defines an outer contour that conforms to an internal contour at a base of the respective cavity, a plurality of cores extending downwardly from each protrusion of the first plurality of protrusions, wherein each core of the plurality of cores is disposed within and extends to the first depth of the respective cavity of the plurality of cavities, and a second plurality of protrusions extending downwardly from the top plate, wherein each protrusion of the second plurality of protrusions forms a seal at the top surface of the bottom block. Example mold assemblies may further include a middle mold portion comprising a wall that forms a seal between the top plate and the bottom block around the periphery of a void space between the top plate and the bottom block.

[0007] Example methods of forming a modular tube apparatus may include the step of providing a bottom mold portion, wherein the bottom mold portion includes a bottom block including a top surface and a plurality of cavities in the bottom block extending downwardly from the top surface to a first depth. Example methods of forming a modular tube apparatus may further include the step of providing a top mold portion, wherein the top mold portion including a top plate positioned opposite and at a first distance from the top surface of the bottom block, a first plurality of protrusions extending downwardly from the top plate to a length less than the first distance, wherein each protrusion of the first plurality of protrusions is disposed opposite a respective cavity of the plurality of cavities, and wherein each protrusion of the first plurality of protrusions defines an outer contour that conforms to an internal contour at a base of the respective cavity, a plurality of cores extending downwardly from each protrusion of the first plurality of protrusions, wherein each core of the plurality of cores is disposed within and extends to the first depth of the respective cavity of the plurality of cavities, and a second plurality of protrusions extending downwardly from the top plate, wherein each protrusion of the second plurality of protrusions forms a seal at the top surface of the bottom block. Example methods of forming a modular tube apparatus may further include the step of providing a middle mold portion, wherein the middle mold portion includes a wall that forms a seal between the top plate and the bottom block around the periphery of a void space between the top plate and the bottom block. Example methods of forming a modular tube apparatus may further include the step of coupling the top mold portion, the middle mold portion, and the bottom mold portion to form a mold chamber. Example methods of forming a modular tube apparatus may further include the step of infiltrating the mold chamber with a molten material. Example methods of forming a modular tube apparatus may further include the step of decoupling and removing the top mold portion.

[0008] These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

[0009] FIGS. **1**A and **1**B depict, respectively, a bottom perspective view and a top perspective view of a modular tube apparatus, according to an example embodiment.

[0010] FIG. **1**C depicts a cross-section view of a modular tube apparatus, according to an example embodiment.

[0011] FIG. **2**A depicts a side perspective view of two modular tube apparatuses, according to an example embodiment, coupled together in series.

[0012] FIG. **2**B depicts a cross-section view of two modular tube apparatuses, according to an example embodiment, coupled together in series.

[0013] FIG. **3** depicts a side perspective view of a top mold portion of a mold assembly, according to an example embodiment.

[0014] FIG. **4** depicts a perspective view of a middle mold portion and a bottom mold portion of a mold assembly, according to an example embodiment.

[0015] FIG. **5** depicts a cross-section view of an assembled mold assembly with a top mold portion, middle mold portion, and bottom mold portion, according to an example embodiment.

DETAILED DESCRIPTION

[0016] Example methods and systems are described herein. It should be understood that the words "example" and "exemplary" are used herein to mean "serving as an example, instance, or illustration." Any embodiment or feature described herein as "example," "exemplary," or "illustrative" is not necessarily to be construed as preferred or advantageous over other embodiments or features. More generally, the embodiments described herein are not meant to be limiting. It will be readily understood that certain aspects of the disclosed methods systems and can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

I. Overview

[0017] Example embodiments herein generally relate to modular tube portions of shell-and-tube heat exchanger apparatuses, and molds and methods for forming the modular tube portions. In a preferred embodiment, a modular tube apparatus for use in a shell-and-tube heat exchanger may include a connecting plate with an arrangement of receiving cups on one side and small diameter long tubes on the other side. The modular apparatus may be configured such that multiple apparatuses may be connected in series with the tubes of one apparatus mating to the receiving cups of the next apparatus in series to form a very long tube assembly with a high-density of small diameter tubes. This beneficially provides a high heat transfer design within a shell-and-tube heat exchanger. Preferably, this type of modular apparatus may be formed as a unitary homogenous body within a casting mold specifically designed to allow the formation of a connecting plate with integral long small diameter tubes. The connecting plate may additionally include one or more through holes to, for example, allow a thermal fluid to flow through the apparatus and aid heat transfer with a working fluid flowing through the tubes.

[0018] FIGS. **1**A, **1**B, **2**A, and **2**B are generally illustrative of an embodiment of the modular tube apparatus. FIGS. **3**, **4**, and **5** are generally illustrative of an example casting mold.

II. Modular Tube Apparatuses

[0019] FIGS. **1**A and **1**B depict a modular tube apparatus **100** for a heat exchanger, according to an example embodiment. Apparatus **100** may include a connecting plate **102** with an arrangement of receiving cups **106** recessed into a top surface of the apparatus **100**. Respective small-diameter long-length tubes **104** may extend downward from the bottom surface of the connecting plate **102**. These tubes **104** may be arranged in the regular pattern as shown, or in other regular or irregular patterns. The plate **102** may be flat as illustrated or may be non-flat. Preferably, the tubes **104** are arranged in a parallel configuration with each other. As discussed with respect to FIG. **2**A, the bottom (distal) ends of the tubes **104** are configured to fit into and mate with the receiving cups **106**, such that multiple apparatuses **100** may be stacked in series to form a long tube assembly with a high-density of tubes for use in a heat exchanger.

[0020] The apparatus **100** is preferably cast as a metal or metal matrix composite with a unitary body in a permanent mold. Preferred metals include, as non-limiting examples, stainless steel alloys Type **304** or Type **316**. The unitary body may be a homogenous casting.

[0021] For purposes of illustrative clarity only, the apparatus **100** is shown with a five-by-five array of tubes **104** for a total of twenty-five tubes **104**. Preferably for a heat exchanger requiring a high heat load, such as one is configured for use in a grid scale energy storage system, a modular tube apparatus, such as apparatus **100**, may have on the order of approximately 10^1, 10^2, 10^3, 10^4, 10^5 or more tubes per apparatus. The use of the five-by-five array is for illustration only and embodiments including up to and beyond 10^5 tubes per apparatus are within the scope claimed herein.

[0022] In the illustrated embodiment, the tubes **104** are preferably formed as substantially cylindrical tubes. Because the apparatus **100** is preferably cast as unitary body in a permanent mold, it may be necessary to include draft on cast parts that must be removed from the permanent mold, and/or on permanent mold portions that must be removed from cast parts. Accordingly, and for purposes herein, the term "substantially cylindrical" should be understood to mean cylindrical with a 0° or greater draft angle along an interior and/or exterior surface that may be in contact with a mold wall surface. For practical purposes, the tubes **104** may have an approximately 1.5° draft angle on either or both the exterior surface and the interior hollow portion. Likewise for the connecting plate **102**. However, depending on the mold constraints, the draft angle may be less than or greater than 1.5° for various parts. The wall thickness of tubes **104** that are cast may be constant or varied along the length of the tube by varying the draft angle between the mold cavity or a respective core. Additionally, draft angles may be varied along the length of the tubes **104**. For illustrative clarity only, and not as a limitation, all draft angles are drawn at 0° in the illustrative Figures.

[0023] Preferably, each of the tubes **104** may be approximately 10 mm or less in width or diameter at the distal end with a length of 100 mm, 500 mm, 1000 mm to 2000 mm or longer. Both smaller and larger diameter tubes **104** are considered and both shorter and longer lengths are considered as well. Length to diameter ratio (or length to width ratio if non-cylindrical) may be tuned for desired thermal transfer properties of the heat exchanger, casting shrinkage and deformation, practical draft angles, or other considerations. For illustrative clarity only, the tubes **104** in FIGS. **1**A, **1**B, and **2**A are shown with a shorter length to diameter ratio than the 50:1. 100:1, and 200:1 ratios described above.

[0024] While cylindrical tubes, and matching cylindrical receiving cups, are preferred shapes of tubes **104** and receiving cups **106** due to fluid flow characteristics, mating requirements (including susceptibility to twist), and heat transfer properties, other shapes are also considered, so long as the distal end of a tube **104** is configured to mate with a receiving cup **106** to form a fluid seal. Non-limiting examples include square, hexagonal, or octagonal tubes. The fluid seal may preferably be formed through the use of a brazing material at one or more mating surfaces of the tubes **104** and receiving cups **106**, but other non-limiting examples may include compression fitting, locking taper with perpendicular compressive force, welding, gasketing, or other configurations.

[0025] A fillet or chamfer **104***a* may be included at the interface of each tube **104** with the bottom surface of the connecting plate **102**. The fillet or chamfer **104***a* may provide strength at that stress-prone area and/or may provide structural material below the receiving cup, as is evident in the cross-sectional view of FIG. **1**C.

[0026] While an internal fluid (e.g., a working fluid) may flow through the apparatus **100** in enclosed paths through receiving cups **106**, internal connecting fluid paths **112** (illustrated in FIG. **1**C), and hollow portions **110** of the tubes **104**, an external fluid (e.g., a thermal fluid) may flow across the tube **104** exteriors. Tubes **104** may include fins or other heat transfer aids along the exterior of the tubes **104**, including straight fins, helical fins, radial fins, and dimples or protrusions, to aid heat transfer between a working fluid and a thermal fluid.

[0027] To enhance and/or allow flow of the external fluid, a second set of fluid paths **108** may extend completely through the connecting plate **102** from the top surface to the bottom surface. The fluid paths **108** may be arranged as shown or in other regular or irregular patterns. Additional or alternatively shaped fluid paths may be added via a mold or other means to optimize the flow of the thermal fluid through the plate **102** to optimize the heat transfer. This may beneficially provide better flow and/or circulation of the external fluid; and, in an embodiment where a shell is sealed to the external periphery of the connecting plate **102**, the fluid paths **108** provide a means of fluid flow between apparatuses, such as apparatus **100**, connected in series.

[0028] FIG. **1**C illustrates a cross-section view of modular apparatus **100**. A break line illustrates that the length **104**L of tubes **104** is preferably much longer than may be practicably depicted in the illustration. Preferably, the tubes **104** have a length **104**L to outside width **104***d* ratio of at least 50:1, 100:1, or 200:1.

[0029] In this illustrated embodiment of modular apparatus **100**, where the tubes **104** are illustrated as substantially cylindrical, the width **104***d* of the distal open end of each tube **104** may also be considered the outer diameter of the tube **104**. Similarly, where the receiving cups **106** are also illustrated as substantially cylindrical, the bottom width **106***d* of the receiving cup **106** may be considered the inside diameter of the bottom of the receiving cup **106**. In other non-cylindrical embodiments, the widths **104***d* and **106***d* may be considered the widths of respective opposing surfaces. For example, for a tube **104** and respective receiving cup **106**, each with a regular polygonal contour, the widths **104***d* and **106***d* may be measured as flat-to-flat, vertex-to-vertex, or flat-to-vertex.

[0030] The distal open end of each tube **104** has an outer contour that conforms to an internal contour of the respective receiving cup **106**. In the illustrated cylindrical embodiment, the outer contour of the distal open end of tube is substantially cylindrical with an outer circumferential surface **116**. Similarly, the internal contour of the respective receiving cup **106** is substantially cylindrical with an internal circumferential surface **114**. The widths **106***d* and **104***d* may be sized such that the internal circumferential surface **114** may form a fluid seal with a mating outer circumferential surface **116**. Brazing may be used to form the fluid seal, though other configurations are considered, as described above.

[0031] Alternatively or additionally, the fluid seal may occur at another surface along the internal and external contours. For example, the fluid seal may occur at a mating interface between the bottom surface of the tube **104** and the annular bottom surface of the receiving cup **106**. Again, brazing may be used to form the seal, though other configurations are considered.

[0032] As shown in FIG. **1**C, each of the receiving cups **106** may be recessed and extend partially through the connecting plate **102** to a distance less than the connecting plate's thickness **102**L at the receiving cups. Each receiving cup **106** may be connected to a hollow portion **110** of the respective tube **104** by a fluid path **112** inside the connecting plate **102**. Preferably each fluid path **112** and hollow portion **110** of the respective tube **104** create a smooth and straight fluid path from the receiving cup **106** to the distal open end of the tube **104**.

[0033] FIG. **2**A illustrates two modular tube apparatuses **100** connected in series, with tubes **104** seated in respective receiving cups **106**. Multiple modular tube apparatuses **100** may accordingly be connected in series to create a very long tube assembly for use in a shell-and-tube heat exchanger. Fluid paths **108** may be present and allow fluid movement not only across the tubes **104** but also through the connecting plates **102**.

[0034] FIG. **2**B illustrates a cross-section view of two modular tube apparatuses **100** connected in series, with tubes **104** seated in respective receiving cups **106**. Break lines illustrate that the tubes **104** are longer than may be practicably illustrated. In an embodiment with substantially cylindrical tubes **104**, outside diameter **104***d* at the distal open end of each tube **104** may be sized to create a fluid seal against the inside diameter **106***d* of receiving cup **106**. Braze or other materials may be used to create the fluid seal. As shown in FIG. **2**B, stacking modular tube apparatuses **100** in series creates a contiguous fluid path through the tubes **104**, allowing for very long fluid paths in small diameter tubes.

III. Molds for Modular Tube Apparatuses

[0035] FIG. **3** illustrates an example top mold portion **300** of a mold assembly **500** (see FIG. **5** for further detail) for casting embodiments of unitary modular tube apparatuses described herein. Top mold portion **300** may include a top plate **302** with protrusions **306** extending downward from the top plate **302**. The protrusions **302** are short and configured to form receiving cups in a modular tube apparatus for a heat exchanger, such as, for example, the receiving cups **106** of the modular tube apparatus **100**. As depicted, the protrusions **306** are substantially cylindrical, but may be any shape as discussed herein with respect to receiving cups.

[0036] Extending downward from the protrusions **306** are cores **304** with a core body **304***a*. The cores **304** are configured to form the hollow portions of tubes in a modular tube apparatus for a heat exchanger, such as, for example, the hollow portions **110** of tubes **104** in the modular tube apparatus **100**, as well as the fluid paths connecting the receiving cups and tubes, such as fluid paths **112**. As depicted, the cores **304** are substantially cylindrical, but may be any shape as discussed herein with respect to tubes. Preferably, the cores **304** are arranged in a parallel configuration with each other. Each core may further include a locating pin **304***b* at the base of the core **304**.

[0037] The top mold portion **300** may also include protrusions **308** extending downward from the top plate **302**. The protrusions **308** are configured to form fluid paths through a connecting plate in a modular tube apparatus for a heat exchanger, such as, for example, the fluid paths **108** through the connecting plate **102** of the modular tube apparatus **100**. As depicted, the protrusions **308** are substantially cylindrical, but they may take other forms as well.

[0038] For purposes of illustrative clarity only, the example mold portions **300** and **400** illustrated in FIGS. **3**, **4**, and **5** are shown with a five-by-five array of cores **304** and receptacles **306** and matching cavities **404** (see FIG. **4** for further detail), for a total of twenty-five tube forming mold sections. Preferably for a large duty heat exchanger, such as one configured for use in a grid scale energy storage system, the mold for a cast modular tube apparatus may have on the order of approximately 10^1, 10^2, 10^3, 10^4, 10^5 or more tube forming mold sections per casting mold. The use of the five-by-five array is for illustration only and embodiments up to and beyond 10^5 tube forming mold sections is within the scope of the claims herein.

[0039] FIG. **4** illustrates an example bottom mold portion **400** of a mold assembly for casting embodiments of unitary modular tube apparatuses described herein. Bottom mold portion **400** includes a bottom block **406** and a top surface **402**. Extending downward from the top surface **402** are cavities **404**. In conjunction with the top mold portion **300**, the cavities **404** are configured to form tubes in a modular tube apparatus for a heat exchanger, such as, for example, the tubes **104** in the modular tube apparatus **100**. As depicted, the cavities **404** are substantially cylindrical, but may be any shape as discussed herein with respect to tubes. Preferably, the cavities **404** are arranged in a parallel configuration with each other. Each cavity **404** may further include a locating receptacle **404***b* at the bottom of the cavity **404**, as illustrated in FIG. **5**. Each cavity **404** may have a chamfer **404***a*, a convex fillet, or other formation configured to provide strength and/or structural material below a molded receiving cup.

[0040] FIG. **4** also illustrates an example middle mold portion **450**. Middle mold portion **450** may take the form of a wall that seals between a component of a top mold portion, for example the top plate **302** of top mold portion **300**, and a component of a bottom mold portion, for example the top surface **402** of bottom mold portion **400**. The middle mold portion **450** may extend around the periphery of a void space that is used to form a connecting plate, for example it may extend around the periphery of a void space between a top plate **102** and a bottom block **406**.

[0041] In the example embodiment depicted in FIG. **4** and FIG. **5**, middle mold portion **450** is depicted as a separate mold portion, but it may also be fixed or unitary with bottom mold portion **400** or fixed or unitary with top mold portion **300**.

[0042] FIG. **5** illustrates an example embodiment of an assembled mold assembly **500**, which may include top mold portion **300**, middle mold portion **450**, and bottom mold portion **400**. Top plate **302** may be positioned opposite and at a distance **450**L above the top surface of bottom block **400**. The positioning forms a void space **502** which forms a connecting plate, such as connecting plate **102**, where the distance **450**L corresponds to a thickness of the connecting plate, with accounting for shrinkage and other dimensional considerations for casting processes. Middle mold portion **450** surrounds the perimeter and seals the void space **502** for the connecting plate.

[0043] Within the connecting plate void space **502**, protrusions **306** extend downward from the top plate **302** to a depth less than the distance **450**L, so as to form receiving cups in a cast connecting plate, such as receiving cups **106** in connecting plate **102**. The protrusions **306** are arranged opposite the cavities **404** in the bottom block **406**. The protrusions **306** define an outer contour that conforms to an internal contour at the base **404***c* of a respective cavity **404**.

[0044] The cores **304** may extend from the bottom of the protrusions **306** to the bottom of the respective cavities **404**, partially defining void spaces **504** and **506**, and forming a fluid path in the casting from the receiving cups **106**, through the connecting plate **102** (e.g., fluid paths **112**), and through the tubes **104** (e.g., hollow portions **110**).

[0045] Each core **304** may include a locating pin **304***b* that mates with a locating receptacle **404***b* at the bottom of the cavity **404** to register the bottom end of the core **304** at a fixed position within the cavity. Preferably, the locating pin **304***b* and locating receptacle **404***b* are matching cones, one in positive relief and one as a cavity. As illustrated, the locating pin **304***b* in shown in positive relief and the locating receptacle **404***b* is shown as a cavity completely filled by the locating pin **304***b*.

[0046] As previously described, bottom block **406** may include a chamfer **404***a* at each cavity **404** opening at the top surface of the bottom block. The chamfer **404***a* partially defines a void space **504** configured to provide strength and/or structural material below the receiving cup **106** in the cast apparatus.

[0047] Protrusions **308** may also extend downward from top plate **302** all the way through the void space **502** and form a seal with the top surface **402** of the bottom block **406**. In the illustrated embodiment, the protrusions **308** may extend to and contact a flat top surface **402** of the bottom block **406** to form through-hole fluid paths in a cast connecting plate, such as fluid paths **108**; however, other configurations are also possible to form through-hole fluid paths through the connecting plate. For example, top surface **402** may include slight recesses into which protrusions **308** seat, while still forming a seal with the top surface **402** around the perimeter of the protrusions **308**.

[0048] Mold assemblies for casting unitary modular tube apparatuses such as mold assembly **500**, are preferably permanent molds, though portions or sections may be non-permanent (e.g., sand casting). To the extent that mold assembly **500** includes permanent mold portions, it may be necessary to include draft on areas that must be separated from the casting. For practical purposes, draft angles may be approximately 1.5°. However, depending on the mold constraints of a particular embodiment, the draft angle may be less than or greater than 1.5°. Accordingly, and for purposes herein, the term "substantially cylindrical" should be understood to mean cylindrical with a 0° or greater draft angle. The void space **506** width between cores **304** and respective cavities **404** may be constant or varied along the length of the tube by varying the draft angle of the cavity **404** or core **304**. Additionally, draft angles may be varied along the length of the cavity **404** or core **304**.

[0049] Preferably, each of the cavities **404** may have a width or diameter **404***d* of approximately 10 mm or smaller in diameter at the bottom with a length **404**L of 100 mm, 500 mm, 1000 mm to 2000 mm or longer. Both smaller and larger widths/diameters **404***d* are considered and both shorter and longer lengths **404**L are considered as well. Length to diameter ratio (or length to width ratio if non-cylindrical) may be tuned for desired thermal transfer properties of the heat exchanger, casting shrinkage and deformation, practical draft angles, or other considerations. For illustrative clarity only, the cavities **404** and cores **304** in FIGS. **3**, **4**, and **5** are shown with a shorter length to diameter ratio than the 50:1. 100:1, and 200:1 ratios described herein. A break line is used in FIG. **5** to illustrate that the lengths are preferably much longer than may be practicably depicted in the illustration.

[0050] Cavities **404**, cores **304**, and matching protrusions **306**, are preferably shaped as substantially cylindrical due to fluid flow characteristics, mating requirements (including susceptibility to twist), and heat transfer properties. However, other shapes are also considered. As long as the distal end of a formed tube may mate with a formed receiving cup to form a fluid seal, other configurations are considered, including the non-limiting examples of square, hexagonal, or octagonal forms.

[0051] In the illustrated embodiment of mold assembly **500**, where the cavities **404** are illustrated as substantially cylindrical, the width **404***d* of the bottom end of each cavity **404** may also be considered the inner diameter of the cavity **404**. Similarly, where the protrusions **306** are also illustrated as substantially cylindrical, the bottom width **306***d* of the protrusions **306** may be considered the outside diameter of the bottom of the protrusions **306**. In other non-cylindrical embodiments, the widths **404***d* and **306***d* may be considered the widths of respective opposing surfaces. For example, regular polygonal contours, the widths **404***d* and **306***d* may be measured as flat-to-flat, vertex-to-vertex, or flat-to-vertex.

[0052] The mold assembly **500** is preferably constructed as a reusable permanent mold and of materials sufficient to withstand repeated high-temperature casting of materials such as metal or metal matrix composites, including stainless steel alloys Type **304** or Type **316**. For example, the mold may be formed as a ceramic mold using laser-based rapid prototyping, a graphite or graphite/metal composite mold, or other rapid prototyping formed mold that may allow the long and thin forms required of the cores and cavities. For metal casting, and particularly stainless steel casting, the mold assembly should be capable of withstanding a casting temperature of approximately 1350° C.

[0053] Various casting methods may be used with the mold assembly **500**. For example, centrifugal, spin, vacuum, low-pressure, liquid metal pumping and high-pressure casting methods may be employed depending on mold design parameters and desired or acceptable finish and/or porosity.

[0054] Risers, gates, vents, sprues/ports and runners may be necessarily and additionally be present in any claimed mold assembly, including mold assembly **500**. Inclusion of some or all of such casting mold structures is considered, though not shown, and such casting mold structures may be included in example mold assembly **500** and other embodiments.

IV. Methods for Casting for Modular Tube Apparatus

[0055] The casting process may be accomplished by providing a mold assembly according to embodiments described herein, coupling together the portions of the mold assembly to form a mold chamber, infiltrating the mold chamber with a molten material, and later decoupling some or all the mold portions in a manner sufficient to remove the cast modular tube apparatus.

[0056] As a specific example method to cast an embodiment of the modular tube apparatus **100** described herein, the following steps may be accomplished.

[0057] A bottom mold portion may be provided. The bottom mold portion may include a bottom block with a top surface. A plurality of cavities in the bottom block may extend downward from the top surface into the interior of the bottom block.

[0058] A top mold portion may be provided. The top mold portion may include a top plate positioned opposite and at a first distance from the top surface of the bottom block. A first plurality of protrusions may extend downward from the top plate to a length less than the first distance. Each protrusion of the first plurality may be disposed opposite a respective cavity of the plurality of cavities. Each protrusion of the first plurality may define an outer contour that conforms to an internal contour at a base of the respective cavity. A plurality of cores may extend downward from each protrusion of the first plurality. Each core may be disposed within the respective cavity and form a respective void space in each cavity. A second plurality of protrusions may extend downward from the top plate. Each protrusion of the second plurality may form a seal at the top surface of the bottom block.

[0059] A middle mold portion may be provided. The middle mold portion may include a wall that forms a seal between the top plate and the bottom block around the periphery of a void space between the top plate and the bottom block.

[0060] The top mold portion, middle mold portion, and bottom mold portion may be coupled together to form a mold chamber. As non-limiting examples, the portions may be bolted or clamped together with internal and/or external bolts or clamps.

[0061] The mold chamber may take the negative form of a modular tube apparatus with or without additional risers, gates, ports, or structural supports, and the negative form be configured to account for shrinkage or growth in the casting material. The mold chamber may be infiltrated with a molten material. Preferably materials include Type 304 or 316 stainless steel.

[0062] Following a dwell period after infiltration, one more mold portions mays be decoupled and removed and then the cast modular tube apparatus removed. In the embodiment illustrated as mold assembly **500**, the top portion **300** with cores **304** may be decoupled and removed, allowing the modular tube apparatus **100** to be removed.

V. Conclusion

[0063] The particular arrangements shown in the Figures should not be viewed as limiting. It should be understood that other embodiments may include more or less of each element shown in a given Figure. Further, some of the illustrated elements may be combined or omitted. Yet further, an exemplary embodiment may include elements that are not illustrated in the Figures.

[0064] Additionally, while various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are contemplated herein.

What is claimed is:

1. A modular tube apparatus for a heat exchanger, the apparatus comprising:

a connecting plate;

a plurality of tubes extending from a bottom surface of the connecting plate, wherein each tube of the plurality of tubes comprises a distal open end and a hollow portion extending from the distal open end to the connecting plate;

a plurality of receiving cups, wherein each receiving cup of the plurality of receiving cups is recessed into a top surface of the connecting plate to a depth partially through the connecting plate and disposed opposite a respective tube of the plurality of tubes, and wherein each receiving cup of the plurality of receiving cups defines an internal contour that conforms to an outer contour of the distal open end of the respective tube of the plurality of tubes;

a first plurality of fluid paths inside the connecting plate, wherein each fluid path of the first plurality of fluid paths extends from each receiving cup of the plurality of receiving cups to the hollow portion of each respective tube of the plurality of tubes; and

a second plurality of fluid paths through the connecting plate, wherein each fluid path of the second plurality of fluid paths extends from the top surface of the connecting plate to the bottom surface of the connecting plate.

2. The apparatus of claim **1**, wherein the apparatus is formed as a unitary body.

3. The apparatus of claim **2**, wherein the unitary body comprises a cast material.

4. The apparatus of claim **3**, wherein the cast material comprises a metal.

5. The apparatus of claim **1**, wherein each tube of the plurality of tubes is substantially cylindrical.

6. The apparatus of claim **1**, wherein proximate to each receiving cup of the plurality of receiving cups, the connecting plate is thicker than the depth of the respective receiving cup.

7. The apparatus of claim **1**, wherein a surface of the internal contour of each receiving cup of the plurality of receiving cups is configured to form a fluid seal with a surface of the outer contour of the distal open end of the respective tube of the plurality of tubes.

8. The apparatus of claim **7**, wherein the fluid seal is formed with a brazing material.

9. The apparatus of claim **7**, wherein the internal contour is substantially cylindrical, wherein the surface of the internal contour is an internal circumferential surface, wherein the outer contour is substantially cylindrical, wherein the surface of the outer contour is an outer circumferential surface, and wherein the internal circumferential surface is configured to form a fluid seal with the outer circumferential surface.

10. The apparatus of **1**, wherein a ratio of a length of each tube of the plurality of tubes to an outside width of the distal open end of each tube of the plurality tubes is at least 50:1.

11. The apparatus of **1**, wherein a ratio of a length of each tube of the plurality of tubes to an outside width of the distal open end of each tube of the plurality tubes is at least 100:1.

12. The apparatus of claim **1**, wherein each tube of the plurality of tubes is parallel to each other tube of the plurality of tubes.

13. The apparatus of claim **1** further comprising a fillet at the interface between each tube of the plurality of tubes and the bottom surface of the connecting plate.

14. The apparatus of claim **1** further comprising a chamfer at the interface between each tube of the plurality of tubes and the bottom surface of the connecting plate.

15. A mold assembly comprising:

a bottom mold portion comprising:

a bottom block comprising a top surface, and

a plurality of cavities in the bottom block extending downwardly from the top surface to a first depth;

a top mold portion comprising:

a top plate positioned opposite and at a first distance from the top surface of the bottom block,

a first plurality of protrusions extending downwardly from the top plate to a length less than the first distance, wherein each protrusion of the first plurality of protrusions is disposed opposite a respective cavity of the plurality of cavities, and wherein each protrusion of the first plurality of protrusions defines an outer contour that conforms to an internal contour at a base of the respective cavity,

a plurality of cores extending downwardly from each protrusion of the first plurality of protrusions, wherein each core of the plurality of cores is disposed within and extends to the first depth of the respective cavity of the plurality of cavities, and

a second plurality of protrusions extending downwardly from the top plate, wherein each protrusion of the second plurality of protrusions forms a seal at the top surface of the bottom block; and

a middle mold portion comprising a wall that forms a seal between the top plate and the bottom block around the periphery of a void space between the top plate and the bottom block.

16. The mold assembly of claim **15**, wherein each cavity of the plurality of cavities comprises a locating receptacle at the first depth, wherein each respective core of the plurality of cores comprises a locating pin at a bottom end of the core; wherein each locating receptacle and each respective locating pin are configured to register the bottom end of each core of the plurality of cores at a fixed position within the respective cavity.

17. The mold assembly of claim **16**, wherein the locating receptacle comprises a cone, and wherein the locating pin comprises a cone.

18. The mold assembly of claim **15**, wherein each cavity of the plurality of cavities is substantially cylindrical.

19. The mold assembly of claim **15**, wherein each core of the plurality of cores is substantially cylindrical.

20. The mold assembly of claim **15**, wherein each core of the plurality of cores is parallel to each other core of the plurality of cores.

21. The mold assembly of claim **15**, wherein each cavity of the plurality of cavities in the bottom block comprises a chamfer at the top surface of the bottom block.

22. The mold assembly of claim **15**, wherein each cavity of the plurality of cavities in the bottom block comprises a convex fillet at the top surface of the bottom block.

23. The mold assembly of claim **15**, wherein a ratio of the first depth to a bottom width of each cavity of the plurality of cavities in the bottom block is at least 50:1.

24. The mold assembly of claim **15**, wherein a ratio of the first depth to a bottom width of each cavity of the plurality of cavities in the bottom block is at least 100:1

25. The mold assembly of claim **15**, wherein the middle mold portion is integral with the top mold portion.

26. The mold assembly of claim **15**, wherein the middle mold portion is integral with the bottom mold portion.

27. A method of forming a modular tube apparatus comprising the steps of:

providing a bottom mold portion, wherein the bottom mold portion comprises: a bottom block comprising a top surface, and a plurality of cavities in the bottom block extending downwardly from the top surface to a first depth;

providing a top mold portion, wherein the top mold portion comprises: a top plate positioned opposite and at a first distance from the top surface of the bottom block, a first plurality of protrusions extending downwardly from the top plate to a length less than the first distance, wherein each protrusion of the first plurality of protrusions is disposed opposite a respective cavity of the plurality of cavities, and wherein each protrusion of the first plurality of protrusions defines an outer contour that conforms to an internal contour at a base of the respective cavity, a plurality of cores extending downwardly from each protrusion of the first plurality of protrusions, wherein each core of the plurality of cores is disposed within and extends to the first depth of the respective cavity of the plurality of cavities, and a second plurality of protrusions extending downwardly from the top plate, wherein each protrusion of the second plurality of protrusions forms a seal at the top surface of the bottom block;

providing a middle mold portion, wherein the middle mold portion comprises: a wall that forms a seal between the top plate and the bottom block around the periphery of a void space between the top plate and the bottom block;

coupling the top mold portion, the middle mold portion, and the bottom mold portion to form a mold chamber;

infiltrating the mold chamber with a molten material; and

decoupling and removing the top mold portion.

* * * * *