

HEAT EXCHANGER WITH HELICAL BAFFLES

BACKGROUND

Technical Field

[0001] The present disclosure is generally directed to heat exchangers, and more particularly, but not exclusively, to heat exchangers implementing helical baffles and increased baffle-to-tube leakage to reduce pressure drop, improve heat transfer coefficient, or both.

Description of the Related Art

[0002] Heat exchangers are generally known and take a variety of forms in the offshore, refinery, power, petrochemical, or paper and food industries, among others. In general, the goal of a heat exchanger is to exchange heat, typically between two working fluids. As the working fluids pass through the heat exchanger, they will lose some pressure. The difference between inlet and outlet pressure may be referred to as the pressure drop. The effectiveness of the heat exchanger at transferring heat between the two working fluids is reflected as a heat transfer rate or a heat transfer coefficient. While some pressure drop is beneficial for providing suitable heat transfer, the general goal for optimal heat exchanger performance is to maximize the ratio of heat transfer to pressure drop because a larger pressure drop increases operating costs of the overall system that includes the heat exchanger. Other design factors include reduced installation and maintenance costs and effective protection against damage from vibration, or loss of efficiency due to fouling.

[0003] One known configuration of a heat exchanger is a shell and tube heat exchanger, as shown in Figure 1. The shell and tube heat exchanger of Figure 1 includes a cylindrical shell 10 that houses a bundle of parallel tubes 11. The tubes 11 extend between two end plates 12. A first fluid 13 flows in and through the space between the two end plates 12 and in contact with the bundle of parallel tubes 11. In other words, the first fluid 13 flows through and internal to the shell 10, but around the outside of the tubes 11. A second fluid flows through and internal to the parallel tubes 11. To provide an improved heat exchange between the two fluids, the flow of the first fluid 13 is defined by intermediate baffles 15 forming respective compartments, which are arranged so that the flow of the first fluid 13 changes its direction in passing from one compartment to the next. The baffles 15, which may be configured as circular segments, are

installed perpendicular to a longitudinal axis 16 of the shell 10 to provide a zigzag flow 17 of the first fluid 13.

[0004] It is well known that a perpendicular position of baffles relative to the longitudinal axis of the shell, as in Figure 1, results in a relatively inefficient heat transfer rate to pressure drop ratio because the baffles produce a large form drag. Adjacent baffles extending parallel to one another and at a right angle with respect to the longitudinal axis of the shell define a cross flow path characterized by numerous sharp turns between adjacent channels. The sharp turns lead to a non-uniform flow and a high pressure drop due at least to form drag, among other factors. The non-uniformity of flow distribution within each segment defined between the adjacent baffles causes numerous eddies, stagnation regions, and expansion/contraction, which decreases a local temperature difference. A further factor contributing to a decreased heat transfer rate is attributed to the fact that the tubes traversed by the first fluid are positioned at a certain radial distance from the shell. Accordingly, the cross flow around the peripherally located tubes is faster than around centrally mounted tubes.

[0005] Thus, conventional baffle arrangement as described above results in flow bypass through baffle-to-shell clearances and flow leakage through tube-to-baffles clearances. Bypass and leakage flow reduces the crossflow heat transfer while the flow maldistribution caused by significant velocity variations increases back-flow and eddies in the dead zones, which in turn leads to the deposition of fouling materials on the outside of the tubes of the bundle of tubes. If the heat exchanger is left to continue operating after disposition of fouling materials within the shell, then a significant loss in performance will be experienced over time, which will translate into an increase in operating cost and consumption of energy. If the heat exchanger is removed from service to be cleaned due to the buildup of fouling materials, there will be a loss or reduction in production, which translates into an increase in operating cost. Further, heat exchangers that are left in a fouled state for too long will develop hardened deposits, which will be difficult to remove and can cause corrosion in local regions with higher temperatures. The bundle of tubes on which the hardened deposits develop and on which corrosion occurs may deteriorate to a point where the bundle of tubes must be removed from service and the damaged tubes are plugged, thereby reducing throughput.

[0006] Furthermore, conventional arrangement of the baffles may experience flow-induced vibration of the tubes since long tubes reaching often 24-feet long are supported by a succession of baffles which, in order to solve the problem associated with the non-uniform velocity, are spaced apart at a substantial distance.

[0007] Helically baffled heat exchangers have been used to overcome the problem of non-uniform flow in shell and tube heat exchangers. A helical pattern of the first fluid flow may allow for a more effective conversion of available pressure drop to heat transfer relative to the example in Figure 1 and may reduce the risk of vibration of the bundle of parallel pipes. However, many helical baffle designs still result in a disadvantageous pressure drop that may increase overall capital and operating costs due to the inclusion of additional compression to account for the pressure drop across the heat exchanger. Prior attempts at reducing the pressure drop across the heat exchanger, such as to increase the space between the baffles, have often resulted in an overall decrease in the heat transfer to pressure drop ratio and thus these prior solutions are likewise disadvantageous.

[0008] In view of the above, it would be advantageous to have a heat exchanger with helical baffles that overcomes the above and other deficiencies and disadvantages of known heat exchangers.

BRIEF SUMMARY

[0009] The present disclosure is generally directed to improving the heat transfer to pressure drop ratio in a heat exchanger with helical baffles. The heat transfer to pressure drop ratio can be improved by maintaining the same or a similar heat transfer coefficient with a reduction in pressure drop, or by maintaining the same or a similar pressure drop and improving the heat transfer coefficient, or some combination thereof. The disclosure contemplates intentionally increasing tolerances of various aspects of the heat exchanger, and particularly increasing the size of selected baffle to tube holes or clearances in a non-limiting example, to decrease resistance for corresponding leakage streams through the heat exchanger. This reduction in resistance has been shown to reduce pressure drop across the heat exchanger while having minimal, if any, impact on the heat transfer rate or heat transfer coefficient. By using an alternating pattern of baffles that include different hole sizes, the tubes through the baffles are sufficiently supported according to industry standards to avoid vibration concerns. Further, the baffle patterns contemplated herein are combined in some cases with a change in the baffle spacing to provide enhanced benefits at least with respect to decreasing pressure drop while maintaining a relatively constant rate of heat transfer, thereby further improving the heat transfer to pressure drop ratio of the heat exchanger.

[0010] More specifically, a heat exchanger may include a shell defining a longitudinal axis. Helical baffles are arranged along a center rod that may be aligned with the longitudinal

axis, with each baffle being at an angle to a plane normal to the longitudinal axis to induce helical flow of a fluid through the shell and around the baffles. The baffles may be spaced from each other by a selected spacing along the center rod and/or longitudinal axis. The helical baffles are arranged along the center rod in an alternating pattern of first and second baffles, meaning a first baffle is followed by a second baffle which is followed by a first baffle and so forth along the center rod and/or longitudinal axis. The first baffles and second baffles each include holes that receive tubes. The holes include first holes and second holes with the second holes having a diameter greater than a diameter of the first holes. Assuming the tubes are all the same size in a non-limiting example, the increased diameter of the second holes increases a clearance between the second holes and the tubes relative to the first holes in the tubes.

[0011] In operation, more fluid can then flow through the second clearances than the first clearances, and the flow through the second clearances is with less resistance and/or less form drag. As a result, the larger second clearances reduce pressure drop across the heat exchanger. At the same time, because the flow through the holes is adjacent the tubes (or where heat transfer takes place), the rate of heat transfer is minimally impacted by the increase in size of the second holes. Thus, the concepts of the disclosure enable a reduction in pressure drop while maintaining a relatively constant rate of heat transfer to improve the overall heat transfer to pressure drop ratio of the heat exchanger relative to conventional heat exchanger constructions.

[0012] Still further, the holes in each baffle are aligned with each other with the first baffles and second baffles generally having an inverse or opposite pattern of holes relative to each other. This means that in locations where the first baffles have small holes, the second baffles have large holes and vice versa. The first holes may also be constructed according to industry standard clearances that reduce or prevent vibration. Thus, the tubes are mechanically supported at the first holes in every other baffle while the intervening baffle includes a larger second hole to assist with increasing leakage flow, as described above. This arrangement allows the unsupported tube length between the first holes to be within industry standards to reduce or prevent vibration. Accordingly, the techniques described herein improve heat transfer to pressure drop ratio of the heat exchanger while also addressing vibration concerns according to industry standards.

[0013] Additional features and advantages of the techniques of the disclosure are described in more detail below.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0014] Figure 1 is a schematic view of flow distribution in a known heat exchanger with perpendicular baffles.

[0015] Figure 2 is an isometric view of an implementation of a heat exchanger with helical baffles according to the present disclosure.

[0016] Figure 3 is an isometric view of a tube bundle associated with the helical baffles of the heat exchanger of Figure 2.

[0017] Figure 4A and Figure 4B are isometric views of isolated helical baffles of the heat exchanger of Figure 2.

[0018] Figure 5 is a schematic illustration of common flow streams in the heat exchanger of Figure 2.

[0019] Figure 6 is an elevational view of a heat exchanger with helical baffles according to the present disclosure.

[0020] Figure 7 is an elevational view of a heat exchanger with helical baffles in a double helix configuration according to the present disclosure.

[0021] Figure 8 is a plan view of baffles with alternating baffle-to-tube clearances of the heat exchangers of the present disclosure.

[0022] Figure 9 is an array of plan views of baffles with different baffle-to-tube hole shapes that may be suitable for the heat exchangers of the present disclosure.

[0023] Figure 10 is a graphical representation of heat transfer and pressure drop performance of the heat exchangers of the present disclosure relative to a conventional heat exchanger.

[0024] Figure 11 is a graphical representation of heat transfer coefficient and Reynolds number of the heat exchangers of the present disclosure.

[0025] Figure 12 is a graphical representation of pressure drop and Reynolds number of the heat exchangers of the present disclosure.

DETAILED DESCRIPTION

[0026] Persons of ordinary skill in the relevant art will understand that the present disclosure is illustrative only and not in any way limiting. Other implementations of the presently disclosed systems and methods readily suggest themselves to such skilled persons having the assistance of this disclosure.

[0027] Each of the features and teachings disclosed herein can be utilized separately or in conjunction with other features and teachings to provide heat exchanger devices, systems, and methods. Representative examples utilizing many of these additional features and teachings, both separately and in combination, are described in further detail with reference to the attached Figures. This detailed description is merely intended to teach a person of skill in the art further details for practicing aspects of the present teachings and is not intended to limit the scope of the claims. Therefore, combinations of features disclosed in the detailed description may not be necessary to practice the teachings in the broadest sense and are instead taught merely to describe particularly representative examples of the present teachings.

[0028] Moreover, the various features of the representative examples and the dependent claims may be combined in ways that are not specifically and explicitly enumerated to provide additional useful implementations of the present teachings. It is also expressly noted that all value ranges or indications of groups of entities disclose every possible intermediate value or intermediate entity for the purpose of original disclosure, as well as for the purpose of restricting the claimed subject matter. It is also expressly noted that the dimensions and the shapes of the components shown in the figures are designed to help understand how the present teachings are practiced but are not intended to limit the dimensions and the shapes shown in the examples in some implementations. In some implementations, the dimensions and the shapes of the components shown in the figures are exactly to scale and intended to limit the dimensions and the shapes of the components.

[0029] The present disclosure is generally directed to improving the heat transfer to pressure drop ratio in a heat exchanger with helical baffles. The heat transfer to pressure drop ratio can be improved by maintaining the same heat transfer coefficient with a reduction in pressure drop, or by maintaining the pressure drop and improving the heat transfer coefficient, or some combination thereof. The disclosure contemplates intentionally increasing tolerances of various aspects of the heat exchanger, and particularly increasing the size of selected baffle to tube holes or clearances in a non-limiting example, to decrease resistance for corresponding leakage streams through the heat exchanger. This reduction in resistance has been shown to reduce pressure drop across the heat exchanger while having minimal, if any, impact on the heat transfer rate or heat transfer coefficient. By using an alternating pattern of baffles that include different hole sizes, the tubes through the baffles are sufficiently supported according to industry standards to avoid vibration concerns. Further, the baffle patterns contemplated herein are

combined with a change in the baffle spacing to provide the benefits discussed herein in at least some non-limiting examples.

[0030] While the present disclosure will proceed to describe certain non-limiting examples of a shell and tube heat exchanger with helical baffles with increased baffle-to-tube (“BTT”) clearance (i.e., varying or increasing a size of the tube holes in the baffles) in select baffles relative to conventional constructions, it is to be appreciated that the concepts of the disclosure can be applied equally to any of the common flow streams and/or clearances in any type of heat exchanger and/or for any type of baffle. Thus, the present disclosure is not limited only to varying BTT clearance in a shell and tube heat exchanger with helical baffles, but rather, can be applied broadly in the heat exchanger context and potentially outside the heat exchanger context as well.

[0031] Figures 1-4B are provided primarily for context and to highlight the benefits and advantages of the concepts of the disclosure. Beginning with Figure 2, a heat exchanger 100 according to one or more implementations of the present disclosure is shown. The heat exchanger 100 may include a shell 102 and a plurality of tubes 104 extending axially through the shell 102. The tubes 104 are best shown in Figure 3. A first fluid passes or flows through the shell 102 and a second fluid passes or flows through the tubes 104. The heat exchanger 100 further includes a plurality of baffles 106, which may be sector-shaped elliptical baffles. In this context only, “sector-shaped elliptical baffles” means that the baffles 106 take the general form of an elliptical or circular sector, which geometrically includes a region bounded by an arc and line segments connecting the center of the ellipse or circle (the origin) and the endpoints of the arc, but may not be inclusive of the entire sector so as to account for other components of the heat exchanger 100 (tubes 104, etc.) and the manner of installation of the baffle 106 (e.g., encompassing or abutting a central tube, or accommodating tubes along the periphery of the elliptical sector, as illustrated in Figures 3 and 4, for example).

[0032] The shell 102 may include an inlet 108 and an outlet 110 to define a flow path through the shell 102 for the first fluid (i.e., the first fluid is received at the inlet 108, passes through the shell 102, and is output at the outlet 110). Each of the baffles 106 may be positioned at an angle 112 relative to a line (N-N) that is normal to a longitudinal axis 114 through a center of the shell 102 in order to guide flow of the first fluid represented by arrows 116 into a helical pattern represented by arrows 118 across the shell 102 from the inlet 108 to the outlet 110. The helical pattern 118 of the first fluid flow 116 may allow for an effective conversion of available pressure drop to heat transfer and reduced risk of vibration because the unsupported tube length

is minimized relative to the conventional heat exchanger in Figure 1, but there can be concerns with pressure drop in the heat exchanger 100, as further described herein. In one or more implementations, there may be no dead spots for fouling along the first fluid flow 116, and the amount of heat transfer may be increased relative to the conventional heat exchanger in Figure 1 due to the elimination of eddies or back mixing. Further, in one or more implementations, a direction of the first fluid flow 116 may be opposite to a direction of a second fluid flow represented by arrows 120 within the tubes 104. In other words, in one or more implementations, the second fluid 120 may flow in a direction that is substantially from the outlet 110 to the inlet 108. Additionally, although the baffles 106, as shown in Figure 2, are flat, in one or more embodiments, opposite sides of each baffle may be curved to guide the first fluid flow 116 along the helical pattern 118.

[0033] Figure 3 provides additional detail of the tubes 104 and baffles 106 of the heat exchanger 100 and illustrates a baffle cage 122 of the heat exchanger 100. With continuing reference to Figure 2, the baffle cage 122 illustrated in Figure 3 may be positioned within the shell 102 of the heat exchanger 100 and generally arranged along the longitudinal axis 114. The baffle cage 122 therefore includes successive baffles 106 positioned at the angle 112 from normal (line N-N in Figure 2) to the longitudinal axis 114 of the baffle cage 122, and the successive baffles 106 may be rotationally and longitudinally offset from each other such that a helical pattern is formed. The rotational offset between successive baffles 106 may be such that at least a proximal radial edge 124 of one baffle 106 overlaps or abuts a distal radial edge 126 of an adjacent baffle 106 in the longitudinal direction.

[0034] Figure 3 illustrates a non-limiting implementation in which the proximal radial edge 124 of each baffle 106 overlaps the distal edge 126 of the successive baffle 106. In one or more implementations, the proximal radial edge 124 of each baffle 106 may be the radial edge of the baffle 106 that is axially closest to the inlet 108 of the shell 102 of the heat exchanger 100, and the distal radial edge 126 of each baffle 106 may be the radial edge of the baffle 106 that is axially farthest from the inlet 108 of the shell 102 of the heat exchanger 100. Further, in one or more implementations, there may be an equal number of baffles 106 per 360 degrees of rotation about the longitudinal axis 114 about which the baffles 106 are disposed. Furthermore, the baffles 106 may support multiple tubes 104 and may guide the first fluid flow 116 in the helical path 118 best shown in Figure 2. Additionally, in one or more implementations, the baffles 106 may be interconnected by a plurality of rods 128. A spacer 130 may optionally be used during

construction to ensure appropriate baffle 106 spacing. As illustrated, spacer 130 is rectangular, although other shapes may be used.

[0035] Still referring to Figure 3, in one or more implementations, each of the baffles 106 may have an outer circumferential edge 132, and each outer circumferential edge 132 may be spaced apart from the outer circumferential edge 132 of an adjacent baffle 106. Each of the baffles 106 may also include the proximal radial edge 124 at one end of the outer circumferential edge 132 and the distal radial edge 126 at the other end of the outer circumferential edge 132 such that the elliptical sector-shaped baffles 106 are defined by the outer circumferential edge 132, the proximal radial edge 124, and the distal radial edge 126. Each of the baffles 106 may have a proximal side 134 and a distal side 136 that are opposite of each other as well as a plurality of spaced apart holes 138 that extend through the baffles 106 from the proximal side 134 to the distal side 136. In one or more implementations, the proximal side 134 of each baffle 106 may be the side of the baffle 106 that is axially closest to the inlet 108 of the shell 102 of the heat exchanger 100, and the distal side 136 may be the side of each baffle 106 that is axially farthest from the inlet 108 of the shell 102 of the heat exchanger 100. One tube 104 of the plurality of axially extending tubes 104 may pass through each of the holes 138 in the baffles 106. In one or more implementations, the holes 138 of one baffle 106 may align with holes 138 on another baffle 106 such that the axially extending tubes 104 may fit through holes 138 and may be supported by multiple baffles 106 over a length of the tubes 104. It is noted that each of the baffles 106 may contain through holes 138 in a selected number and arrangement even if Figure 3 illustrates only some baffles 106 containing holes for convenience.

[0036] In an implementation, the tubes 104 and through holes 138 do not extend all the way to the outer circumferential edge 132 of the baffles 106. Thus, when installed within the shell 102, a gap would be present between the shell and the outermost tubes 104. The baffle cage 122 may include a plurality of seal rods or seal strips 140 disposed at an angle such that the fluid flowing through the shell 102 is, at least in part, directed back towards the tubes 104. Seal strips 140 may thus provide a dual function of enhanced sealing and structural support, decreasing the amount of fluid that may bypass the plurality of tubes 104 as well as supporting the structure of the cage 122. In some implementations, the seal strips 140 may be optional and are omitted. The rods 128 described above are likewise optional and may be used to support the baffles 106 during insertion of the tubes 104. Although rods 128 are shown to interconnect the baffles 106 in Figure 3, in one or more implementations of the present disclosure, rods 128 are

not necessary to support and interconnect the baffles 106. Instead, strips may be used to support and interconnect the baffles 106 about a center rod in at least some implementations.

[0037] Turning to Figures 4A and 4B, illustrated therein are isolated baffles 106 of the heat exchanger 100. With continuing reference to Figure 2 and Figure 3, the baffles 106 may be coupled to a center rod 142 within the shell 102 of the heat exchanger 100. Successive baffles 106 may be positioned at the angle 112 from normal (line N-N in Figure 2) to a longitudinal axis 144 of the center rod 142. In some implementations, the longitudinal axis 144 of the center rod 142 is aligned with the longitudinal axis 114 of the shell 102 best shown in Figure 2 or the longitudinal axis 144 may be offset from the longitudinal axis 114 of the shell 102 depending on installation location of the center rod 142 and/or baffle cage 122. Figure 4A and Figure 4B also provide additional detail regarding the baffles 106, including the proximal radial edge 124, the distal radial edge 126, the outer circumferential edge 132, proximal side 134, distal side 136, and the holes 138 that extend through the baffles 106.

[0038] Additionally, in one or more embodiments, each of the baffles 106 may include a center hole 146 at an intersection between the proximal radial edge 124 and the distal radial edge 126 through which the center rod 142 may pass in order to couple each of the baffles 106 to the center rod 142. The center hole 146 of each baffle 106 may be uniquely angled such that the baffles 106 are positioned at the angle 112 from normal (line N-N in Figure 2) to the longitudinal axis 144 of the center rod 142, which may align with the longitudinal axis 114 of the heat exchanger shown in Figure 2. Further, in some implementations the baffle angle 112 may vary along the length of the heat exchanger 100, such as where proximal baffles 106 are disposed at a first angle to the longitudinal axis 114, 144 and more distal baffles 106 are disposed at a different angle to the longitudinal axis 114, 144. As another example, proximal baffles 106 may be disposed at a first angle to the longitudinal axis 114, 144 and more distal baffles 106 may be successively disposed at increasing or decreasing angles to the longitudinal axis 114, 144.

[0039] Figure 5 is a schematic illustration of common flow streams in the heat exchanger 100 and illustrates a plan view of the heat exchanger 100 (left image) and an elevational view of the heat exchanger 100 (right image). While the images of Figure 5 include flow streams through only a portion of the heat exchanger 100, it is to be appreciated that the flow streams through the remainder of the heat exchanger 100 may behave similarly. The common flow streams through the heat exchanger 100 include stream A, stream B, stream C, stream E, and stream F, all of which are illustrated in Figure 5. Stream A is a leakage stream generated by a clearance between the tubes 104 and the holes 138 in the baffles 106. Stream A may also be

referred to as the leakage stream associated with BTT (baffle-to-tube) clearance referenced above. Stream B is the main stream flowing across the tubes 104 and may be equivalent to the helical flow 118 through the exchanger 100 described above with reference to Figure 2. Stream C is a leakage stream between an outer surface or outer limit of the tubes 104 and an inner wall 148 of the shell 102. Stream E is a leakage stream between the baffles 106 and the inner wall 148 of the shell 102, or between the outer circumferential edge 132 of the baffles 106 and the inner wall 148 of the shell. Stream F is a leakage stream around the center rod 142 (Figure 4A) of the baffle cage 122. In other words, Stream F is a leakage stream associated with the clearance between the baffles 106 and the center rod 142 (Figure 4A).

[0040] The streams A, C, E, and F may also be collectively referred to as leakage streams while stream B, which is the main stream or helical flow 118, may be referred to as the main stream. The relative flow in at least each of the leakage streams A, C, E, and F depends on the tolerances which the tubes 104, baffles, 106 and shell 102 are constructed. The flow through the leakage streams A, C, E, and F may also impact flow through the main stream B. In some implementations, the performance of the heat exchanger 100 may be sensitive to the tolerances to which the heat exchanger 100 is built. For example, if tolerances on the clearance between the baffle 106 and the shell 102 are decreased or are tighter, the pressure drop across the heat exchanger 102 will increase, but the heat transfer rate does not necessarily increase. As described above, the conventional understanding is that the leakage streams A, C, E, and F reduce crossflow heat transfer while flow maldistribution caused by significant velocity variations increases back-flow and eddies in the dead zones. The helical nature of the baffles 106 described herein resolves many of the concerns regarding flow maldistribution relative to conventional perpendicular baffle arrangements. However, in view of the understanding that leakage streams A, C, E, and F reduce heat transfer rate, presumably by reducing flow through the main stream B, prior solutions for shell and tube heat exchangers, such as heat exchanger 100, have aimed to reduce the tolerances, thereby reducing the flow through the leakage streams A, C, E, and F, or by introducing additional structures that aim to prevent flow through the leakage streams A, C, E, and F and/or to redirect the leakage streams A, C, E, and F to the main stream B. While such solutions may improve heat transfer rate, they also result in an increase in pressure drop because of factors such as form drag over the baffles 106 and back eddies, among others. As a result, prior solutions do not necessarily achieve a meaningful improvement in the heat transfer rate to pressure drop ratio.

[0041] Industry standards for heat exchanger construction, such as those put forth by the Tubular Exchanger Manufacturers Association (“TEMA®”), are a further design consideration. TEMA® is an industry body which sets standards and tolerances for heat exchanger construction. For helical baffles, such as baffles 106, TEMA® indicates that the BTT clearance be 1/32 inch where the maximum unsupported tube 104 length is 36 inches or less (or for tubes 104 larger in diameter than 1-1/4 inches). If the unsupported tube 104 length exceeds 36 inches for tubes 104 that are 1-1/4 inches diameter and smaller, the BTT clearance should be 1/64 inch over the outer diameter of the tubes 104. These tolerances are set with the goal of reducing vibration of the tubes 104. TEMA® also has standards concerning the maximum unsupported straight tube spans that vary based on an outer diameter of the tubes and tube material and temperature limits. Such standards range from a maximum unsupported length of 22 inches for certain types of 1/4 inch tubes to 125 inches for larger tubes (2 inches and above), again with specific materials. Thus, the maximum unsupported straight tube span may generally vary from 22 inches to 125 inches depending on the characteristics of the tubes 104. Where the tubes 104 are 3/8 inch tubes 104, as provided in some non-limiting examples herein, the maximum span may be 30 inches or 35 inches depending on the type of material selected for the tubes 104. Industry software modeling systems may have options where tube holes can be two times larger (i.e., 1/16 inch) than the TEMA® standards above for all holes, but this is generally not a recommended practice because of vibration concerns. As a result, it is not commonly thought in the industry that increasing the BTT clearance is a viable solution. In fact, prior industry publications have indicated that increases in the BTT clearance can actually result in a decrease in heat transfer rate in certain applications, which in combination with the vibration concerns discussed above, has resulted in the industry generally avoiding increasing tolerances and instead attempting other solutions with minimal benefit.

[0042] Figure 6 is an elevational view of a heat exchanger 200 according to one or more implementations of the present disclosure. Figure 7 is an elevational view of a heat exchanger 201 according to one or more implementations of the present disclosure. Figure 8 is a plan view of alternating baffles 202 of the heat exchangers 200, 201. Beginning with Figure 6, the heat exchanger 200 may include helical baffles 202 that are spaced apart from each other along a longitudinal axis 204. The longitudinal axis 204 may also represent a center rod 204 of the heat exchanger 200, similar to center rod 142 described above. The baffles 202 are generally arranged in a helical pattern to induce helical flow of the main stream B similar to the helical flow 118 of Figure 2. The heat exchanger 200 in the illustrated implementation includes thirteen

baffles 202 which each include four separate and spaced apart sections or “quadrants” that are best shown in Figure 4A (i.e., Figure 4A illustrates the four quadrants of one baffle). Thus, the first baffle 202 includes quadrants A1, B1, C1, and D1, the second baffle 202 includes quadrants A2, B2, C2, and D2, and so on for each of the thirteen baffles 202. The quadrants of each baffle 202 may be spaced from each other about a center rod to define the helical flow. The number and arrangement of the baffles 202 may generally be selected and may be different than the arrangement of Figure 6. In some implementations, helical flow might also be achieved with other techniques, such as by using more sectors rather than quadrants. The techniques discussed herein can be applied to other baffle arrangements for inducing helical and other types of flow.

[0043] The heat exchanger 200 further includes end plates 206 to provide additional support for the tubes. In an implementation, a distance D1 between the end plate 206 and a center of the first baffle 202 is between 3.5 and 4.5 inches and may be 4.0781 inches in a preferred implementation. A distance D2 between the center of the first baffle 202 and a center of the last baffle 202 is between 30 and 37 inches and is preferably 33.5 inches in the illustrated implementation. A distance D3 between successive baffle segments is between 2.5 and 3.5 inches and is preferably 2.9 inches in the illustrated implementation. Finally, a distance D4 between a center of the last baffle 202 and the end plate 206 at the opposite end of the heat exchanger 200 is between 2.25 and 3.25 inches and is preferably 2.7156 inches in the illustrated implementation. It is to be appreciated that the above dimensions are provided only to illustrate the concepts of the disclosure rather than to limit the disclosure to the specific dimensions stated. In practice, the above dimensions D1-D4 can generally be selected and may be more or less than the stated ranges. Further, the dimensions above are in inches and represent a test heat exchanger to illustrate the techniques discussed herein. In practice, the heat exchanger 200 may be much larger (i.e., 10, 20, 30 or more feet in length) and thus the dimensions and numbers of baffles 202 may vary as the techniques discussed herein are implemented in production scale heat exchangers 200.

[0044] In the heat exchanger 200, the dimension D3 that represents the spacing between baffles 202 or baffle overlap is increased relative to the heat exchanger 100. For example, the heat exchanger 100 may include sixteen baffles with a baffle overlap of 58.8% (i.e., reduced baffle spacing) while the heat exchanger 200 includes thirteen baffles 202 with an overlap of 73.3%. In various implementations, the baffle overlap may be at least 40%. Further, a baffle angle of the baffles 202 relative to a plane normal to the longitudinal axis 204 (i.e., similar to angle 112 in Figure 2) may be 7 degrees and may be consistent for all baffles 202 in a non-

limiting implementation. In some non-limiting examples, the baffle angle may be between 5 degrees and 45 degrees. While the increased spacing of the baffles 202 may be expected to result in some reduction in pressure drop, it is noted that there is a relationship between pressure drop and throughput or flow rate through the heat exchanger 200. Specifically, higher flow rates are associated with an increased pressure drop relative to lower flow rates because the factors discussed herein, such as form drag, back eddies, and others, are more significant at higher flow rates. Thus, where a heat exchanger has a lower pressure drop relative to conventional solutions, a higher flow rate can be provided through the heat exchanger without a net increase in pressure drop relative to conventional solutions, which increases yield and overall efficiency of the heat exchanger. Still further, conventional understanding suggests that the increase in baffle spacing of the heat exchanger 200 will result in a reduction in heat transfer rate because of the reduced interaction of the helical flow of the main stream B with the tubes supported by the baffles 202. However, as discussed further below, the techniques of the disclosure allow for a significant reduction in pressure drop associated with the heat exchanger 200 while maintaining a relatively constant heat transfer rate, thereby drastically improving the ratio of heat transfer to pressure drop.

[0045] Figure 7 is an elevational view of heat exchanger 201. In addition to the helical baffles 202, the heat exchangers of the disclosure may also have baffles 203 arranged in a double helix pattern as shown in Figure 7. In other words, the heat exchanger 200 includes only one or a single set of helical baffles 202 while the heat exchanger 201 includes a second set of helical baffles with the two sets of baffles 203 arranged in a double helix configuration. The double helix baffles 203 may be advantageous to reduce tube span if desirable in certain designs. The double helix baffles 203 may have similar spacing and angular orientation to the baffles 202 described herein, or may be different to account for the different spacing in the double helix configuration. Except as otherwise noted below, the baffles 203 may be similar to the baffles 202 (or 202A, 202B) described further with reference to the heat exchanger 200. While single helical baffles or a double helix configuration are preferred, the benefits of the disclosure may also be obtained through other baffle configurations beyond a single set of helical baffles or a double helix configuration. Thus, the disclosure is not limited to the particular number and arrangement of the baffles illustrated in Figure 6 and Figure 7.

[0046] Figure 8 illustrates two plan views of alternating baffles 202A, 202B in the heat exchanger 200 of Figure 6. In an implementation, the baffles 202A, 202B may also be the helical baffles of the heat exchanger 201 in Figure 7. With continuing reference to Figure 6 and

Figure 7, the baffles 202 include holes 208 to receive tubes that may have a diameter that varies across each baffle 202. The holes 208 of each baffle 202 are aligned with corresponding holes in the preceding and/or successive baffles 202 to support the tubes in a straight axial line in some non-limiting implementations, such as tubes 104 shown and described above. The holes 208 are generally arranged in a selected number of rows and columns in each baffle 202 with at least some spacing between the holes 208 to maintain structural integrity of the baffles 202. In a non-limiting implementation, each baffle 202 preferably includes holes 208A and holes 208B that have different diameters. The holes 208A are shown in white and the holes 208B are shown in grey. The holes 208A may have a diameter of 0.40625 inches such that when a 3/8 inch (0.375 inches) tube is inserted through the holes 208A, the clearance is 1/32 inches or TEMA® standard clearance. The holes 208B may have any diameter greater than 0.40625 inches and preferably 0.465 inches such that when a 0.375 inches tube is inserted through holes 208B, the clearance is 0.09 inches. A clearance of 0.09 inches is a 188% increase in size relative to TEMA® standard clearance and thus represents a significant increase in the size of the holes 208B and corresponding clearance relative to TEMA® standards.

[0047] As shown in Figure 8, the holes 208A, 208B are arranged in an alternating pattern across each baffle 202 meaning that each hole 208A is adjacent to larger holes 208B and vice versa, except as otherwise provided herein. Other configurations of the holes 208A, 208B beyond an alternating pattern are contemplated herein, including at least a random selection of larger and smaller holes 208A, 208B, gradients of larger to small holes across the baffles 202, and others. In the heat exchangers 200, 201 the baffles 202 are arranged in an alternating and repeating pattern of the baffles 202A and 202B shown in Figure 8. In other words, baffle 202A may be representative of all the odd-numbered baffles 202 and associated quadrants (i.e., A1, A3, B1, B3, etc.) and baffle 202B may be representative of all the even-numbered baffles 202 and associated quadrants (i.e., A2, A4, B2, B4, etc.) of the heat exchanger 202. Importantly, the pattern of holes 208A, 208B also alternates between each baffle 202A, 202B, meaning that in locations where baffle 202A includes smaller holes 208A, baffle 202B includes larger holes 208B, as illustrated in Figure 8. The first hole 208 in the upper left of the B quadrant of baffle 202A is a larger hole 208B. The corresponding hole 208 in the baffle 202B is a small hole 208A and so forth. As a result, the tubes that are inserted through the holes 208 are mechanically supported at every other baffle 202 with a TEMA® standard hole and clearance (i.e., holes 208A) with the middle, intervening baffle including a larger hole (i.e., hole 208B) that may not provide mechanical support for the tubes, but allows for an increase in flow of the leakage

stream A described above. Using the non-limiting example dimensions provided in Figure 6, this means that the tubes are supported by the holes 208A at 5.8 inches in compliance with TEMA® standards to address vibration concerns.

[0048] While Figure 8 illustrates the baffles 202A, 202B in plan view, in practice, the baffles 202A, 202B are separated along dashed lines 210 in Figure 8. In a non-limiting implementation, the baffles 202A, 202B include an outermost series of holes 208 along the segmentation lines 210 (i.e., an outermost series of holes 208 relative to an outer edge of the baffles 202A, 202B) that are the same diameter instead of the alternating pattern described above. Such an arrangement may be beneficial for drilling of the holes 208 and may also help to define the alternating pattern, but are not required. In some implementations, the outermost series of holes 208 likewise has the alternating pattern of smaller and larger holes 208A, 208B described herein. For similar reasons, all of the holes proximate a center of each baffle 202A, 202B may be the same size. Instead of the alternating arrangement of holes 208 with different diameters in each alternating baffle 202A, 202B described above, the baffles 202A, 202B may each include only holes of a single, consistent diameter. For example, in a non-limiting implementation, baffle 202A may only have holes 208A while baffle 202B may only have holes 208B. While the alternating arrangement of holes 208 shown in Figure 8 is preferred for efficiency in the drilling of the holes 208, other configurations and arrangements of the holes are possible and contemplated herein. In some implementations, the arrangement and characteristics of the holes 208 in the baffles 202 of the disclosure may result in an open area of the baffles 202 that is between 6% and 20%, and more preferably about 10%. In contrast, a baffle constructed only with TEMA® standard holes (i.e., only 1/32 clearance) has an open area of about 5%. Thus, adding the holes 208B nearly doubled the open area of the baffles 202 contemplated herein while enabling sufficient support for compliance with TEMA® standards and prevention (or reduction) of vibration.

[0049] In sum, the present disclosure contemplates increasing the BTT clearance, as described above with reference to Figures 6-8, in order to intentionally increase leakage stream A. Typically, it would be expected that increasing any of the leakage streams A, C, E, F, including leakage stream A, would result in a reduction in heat transfer. Because the leakage stream A flows in the vicinity of the tubes (such as tubes 104) where heat transfer takes place, it has been found that increasing the BTT clearance minimally impacts heat transfer rate within a given range. Further, increasing the BTT clearance at least in part assists with reducing pressure

drop through the heat exchangers 200, 201, thereby improving the overall heat transfer to pressure drop ratio of the heat exchangers 200, 201.

[0050] Figure 9 is an array of plan views of baffles 202 (or baffles 203) with different baffle-to-tube hole shapes that may be suitable for the heat exchangers described herein. As noted above, the present disclosure contemplates different arrangements and characteristics of the holes 208 of the baffles 202, including at least with respect to the shape of the holes 208. The shape of the holes 208 may generally be selected and may include at least square or quadrangular holes (upper left image), hexagonal cinquefoil holes (upper middle image), trefoil holes (upper right image), round holes (lower left image), and reticulated holes (lower right image). Other shapes are possible, such as at least elliptical holes, oval holes, polygonal or polyhedral holes with a selected number of sides, trapezoidal holes, and others. Instead of varying the hole diameters across the baffles 202 as in Figure 8, it may also be possible to use only holes 208 with standard TEMA® clearance (i.e., only holes 208A in the baffles 202) and add holes 212 (leakage holes 212) of a selected shape, such as any shape described herein and others, between the TEMA® holes 208, as shown in dashed lines in the lower left image of Figure 9. Such holes 212 may be larger, smaller, or the same size as the holes 208 for the tubes, although because of the space available, the holes 212 may preferably be smaller. In an implementation, the holes 212 are provided in the baffles 202 in a selected number and arrangement (i.e., between all or only some of the holes 208) and may not support tubes. The above and other alternatives of the holes 208 are contemplated herein and thus the disclosure should not be limited with respect to the arrangement or characteristics of the holes 208.

[0051] Figure 10 is a graphical representation of heat transfer and pressure drop performance of the heat exchanger 200 (“run 112”) relative to a comparative implementation 214 (“run 89”). The performance of the heat exchanger 201 may be similar to the heat exchanger 200 in some implementations, as the double helix configuration does not appreciably change heat transfer and/or pressure drop, but rather, reduces tube span. The heat exchanger 200 may generally be constructed as described with reference to Figure 6 and Figure 8, meaning that the baffles 202 are alternating baffles 202A, 202B with holes 208 with alternating diameters (i.e., holes 208A, 208B) and at an increased spacing or overlap of the baffles 202 of preferably 73.3%. The comparative implementation 214 may be constructed as described in the comparisons above, namely for a similarly sized heat exchanger as heat exchanger 200, there are sixteen baffles with a baffle overlap of 58.8% (i.e., reduced baffle spacing) and the holes in the baffles are only drilled for standard TEMA® clearance (i.e., only holes 208A in the baffles 202) with the tubes.

In both the heat exchanger 200 and the comparative implementation 214, the tubes were 3/8-inch tubes as in the above non-limiting examples and the baffle angle was the same for all baffles. Other aspects of the heat exchanger between the two test examples were similar in all tests unless otherwise noted.

[0052] Figure 10 illustrates the results of various flow rates of the same fluid, which may be water in a non-limiting example, through the two test heat exchangers described above. On the left vertical axis or left Y-axis is heat transfer coefficient measured in Watt per square meter and Kelvin (“W/m²K”) and on the right vertical axis or right Y-axis is pressure drop measured in pounds per square inch (“PSI”). Notably, the pressure drop is change in pressure or delta pressure across the example heat exchangers. The X-axis provides the flowrate through the exchangers in gallons per minute (“GPM”). Lighter circles 216 on the graph correspond to heat transfer coefficient for the heat exchanger 200 and darker circles 218 are for heat transfer coefficient for the comparative implementation 214. Lighter squares 220 are pressure drop for the heat exchanger 200 and darker squares 222 correspond to pressure drop for the comparative implementation 214 of a heat exchanger. As can be seen in Figure 10, the heat transfer coefficient and pressure drop of the comparative heat exchanger 214 increased with flow rate with pressure drop generally increasing in an exponential manner (i.e., rate of increase of pressure drop increased with higher flow rates). As a result, the ratio of heat transfer coefficient to pressure drop was generally consistent at various flow rates, although at higher flow rates, the ratio may decrease because of the factors discussed herein that tend to increase pressure drop at higher flow rates. While the heat exchanger 200 exhibited a similar overall trend of increasing pressure drop with higher flow rates, as expected, the increase in pressure drop at higher flow rates for the heat exchanger 200 was considerably less than the increase in pressure drop for the comparative implementation. Further, the increase in pressure drop for the heat exchanger 200 exhibited more linear behavior at a lower or less steep slope as opposed to the exponential increases seen in the comparative example 214. Perhaps more surprisingly, the heat transfer coefficient of the heat exchanger 200 remained similar relative to the comparative implementation 214 despite the significant reduction in pressure drop across various flow rates. As a result, the heat exchanger 200 had a much higher and more advantageous heat transfer to pressure drop ratio at all flow rates, and particularly at higher flow rates where pressure drop more rapidly increased for the comparative implementation 214.

[0053] Using approximate values from the graph of Figure 10, the pressure drop for the heat exchanger 200 at 100 GPM flow rate was approximately 0.5 PSI. The pressure drop for the

comparative implementation at the same flow rate was approximately 2.75 PSI. Expressed another way, the percentage decrease in pressure drop associated with the heat exchanger 200 was around 81.8% relative to the comparative implementation 214 constructed with conventional techniques. In other test examples, the percentage decrease in pressure drop was approximately 50%. The improvement in pressure drop is attributable, at least in part, to each of the increased baffle spacing and the increased BTT clearance that increases flow through leakage stream A. Simulations were also conducted with the baffle spacing the same between two test cases (i.e., the only difference being the BTT clearance), and the results were generally similar in the sense that heat transfer was the same and a pressure drop was achieved in the heat exchanger with increased BTT clearance. The relatively constant heat transfer coefficient between the two examples is a surprising result given the general industry understanding that increasing leakage streams, such as leakage stream A, will reduce heat transfer. It is believed that the increased flow in the leakage stream A does not meaningfully reduce heat transfer since it flows in the vicinity of the tubes where heat transfer takes place. With respect to the baffle spacing, the increase in spacing will tend to increase the proportion of the leakage stream F along the center holes of the baffles (i.e., along the center rod), but again, the leakage stream F may not meaningfully reduce heat transfer since there are some tubes in the vicinity of the center rod, as shown and described above.

[0054] Figure 11 is a graphical representation of heat transfer coefficient and Reynolds number of the heat exchangers of the present disclosure. The Reynolds number (Re) is a dimensionless quantity that helps predict fluid flow patterns by measuring the ratio between inertial and viscous forces. At low Reynolds numbers, flows tend to be turbulent, while at higher Reynolds numbers, flows tend to be laminar. In Figure 11, the light grey circles 224 correspond to a heat exchanger with 58% baffle overlap and double TEMA® clearance for the tubes relative to the baffles. The dark squares 226 are for a heat exchanger with 58% baffle overlap and standard or single TEMA® clearance. The dark circles 228 are for a heat exchanger 72% baffle overlap for double TEMA® clearance and the light gray squares 230 are for a heat exchanger with 72% baffle overlap for a variable clearance, meaning the tube holes in the baffles may have a variety of selected and different clearances.

[0055] A heat exchanger with standard TEMA® clearance represented by dark squares 226 demonstrates a logarithmic function for flows from a low to high Reynolds number, meaning that while the heat transfer coefficient increased for flows with a higher Reynolds number, the rate of change of the heat transfer coefficient decreased or became more linear for

higher Reynolds number flows. A heat exchanger with variable clearance 230 illustrated similar behavior, but had a notably higher heat transfer coefficient for more turbulent flows or lower Reynolds number flows relative to the heat exchanger with standard TEMA® clearance. Thus, heat transfer performance of the heat exchanger with variable clearance 230 improved relative to the heat exchanger with standard TEMA® clearance 226 for more turbulent flows. Both the heat exchangers with double TEMA® clearance 224, 228 exhibited more linear behavior with heat transfer coefficient increasing as the Reynolds number increases. Of the test samples, the heat exchanger with 58% baffle overlap and double TEMA® clearance had the highest heat transfer coefficient for a flow with a high Reynolds number. The linear nature of the results for the heat exchangers with double TEMA® clearance generally suggests that the heat transfer coefficient can be improved across flows with various Reynolds numbers, as the heat exchangers do not experience a reduction in the rate of change of the heat transfer coefficient for flows with a higher Reynolds number (i.e., more laminar flows).

[0056] Notably, although the behavior of each heat exchanger was slightly different, the heat transfer coefficient for a flow with a given Reynolds number was relatively similar or constant despite the increase in the baffle to tube clearance. In other words, the heat exchangers of the disclosure did not exhibit a significant drop in heat transfer coefficient across a variety of flows despite the increased baffle to tube clearance, but rather, demonstrated relatively constant heat transfer coefficient across a variety of different flows. The heat exchanger with variable clearance 230 most closely resembled the data for the heat exchanger with standard TEMA® clearance 226, which may suggest that this design is particularly advantageous for providing the benefit of a reduction in pressure drop described herein while maintaining the heat transfer coefficient associated with a conventional design.

[0057] Figure 12 is a graphical representation of pressure drop and Reynolds number of the heat exchangers of the present disclosure. The same four heat exchangers were tested in Figure 12 as described above in Figure 11. The heat exchanger with standard TEMA® clearance 226 displayed an exponential increase in pressure drop in relation to flows with an increasing Reynolds number. While the other heat exchangers 224, 228, 230 likewise displayed exponential behavior, the rate of change (or rate of increase) for these heat exchangers 224, 228, 230 was lower than the rate of change (or rate of increase) for the heat exchanger with standard TEMA® clearance 226. Thus, for a flow with a given Reynolds number, the pressure drop is demonstrated to be lower in the heat exchangers 224, 228, 230 than in the heat exchanger with standard TEMA® clearance 226. Figure 12 further supports that the concepts of the disclosure

enable a reduction in pressure drop across flows with a variety of characteristics (i.e., Reynolds number, which is calculated based at least one fluid density, fluid velocity, and fluid viscosity) relative to a conventional heat exchanger with standard TEMA® clearance.

[0058] In combination, Figure 11 and Figure 12 demonstrate that the heat exchangers of the disclosure perform similarly (in some cases better) than a conventional heat exchanger with standard TEMA® clearance while also experiencing a significant reduction in pressure drop across a variety of flows with different characteristics.

[0059] In view of the above, the techniques discussed herein reduce pressure drop across a heat exchanger while maintaining a relatively constant heat transfer coefficient to improve the overall heat transfer to pressure drop ratio of the heat exchanger. The improvement in pressure drop saves costs elsewhere in the system by reducing equipment count and operating costs associated with compression and the hydraulic system for cooling water, among others. In addition, lower pressure drop may result in lower operating costs for the exchanger itself. The concepts of the disclosure also enable an improvement in heat transfer, such as, for example, by adjusting characteristics of the heat exchanger that tend to increase heat transfer and pressure drop. For example, the helix angle or baffle angle can be increased, which tends to increase heat transfer and pressure drop. But, with the concepts of the disclosure, the reduced pressure drop offsets the increase from the different helix angle, thereby resulting in an exchanger with improved heat transfer at a relatively similar pressure drop to prior solutions. In some cases, various characteristics and factors can be balanced to improve both heat transfer and pressure drop. Because of the reduced pressure drop, the flow rate through the exchanger can be higher, which increases yield and overall efficiency and efficacy of the heat exchanger. At the same time, the techniques discussed herein keep the maximum unsupported span of the tubes below TEMA® standards.

[0060] In one more implementations, a heat exchanger may be summarized as including: a shell having a longitudinal axis; a plurality of helical baffles inside the shell and arranged along the longitudinal axis in an alternating pattern of a first baffle followed by a second baffle of the plurality of helical baffles; a plurality of holes in the plurality of helical baffles, the plurality of holes including first holes having a first diameter and second holes having a second diameter greater than the first diameter; and a plurality of tubes received in the plurality of holes in the plurality of baffles.

[0061] In an implementation, a clearance between the plurality of tubes and the first holes is approximately 1/32 inch.

[0062] In an implementation, a clearance between the plurality of tubes and the second holes is greater than 1/32 inch.

[0063] In an implementation, a clearance between the plurality of tubes and the second holes is at least 1/16 inch.

[0064] In an implementation, the first holes in the first baffle are aligned with the second holes in the second baffle.

[0065] In an implementation, the second holes in the first baffle are aligned with the first holes in the second baffle.

[0066] In an implementation, the first holes and the second holes of the plurality of helical baffles are arranged in an alternating pattern.

[0067] In an implementation, a baffle overlap between successive baffles of the plurality of helical baffles is at least 40%.

[0068] In an implementation, the plurality of holes includes an outermost series of holes in the plurality of helical baffles each having a same diameter.

[0069] In an implementation, the plurality of helical baffles are arranged at an angle to a plane normal to the longitudinal axis between 5 degrees and 45 degrees.

[0070] In an implementation, the plurality of holes are round holes, square or quadrangular holes, hexagonal cinquefoil holes, trefoil holes, or reticulated holes.

[0071] In an implementation, the shell and the plurality of helical baffles are configured to assist, at least in part, in defining a main flow path through the shell and a clearance between the plurality of holes and the plurality of tubes is configured to define a flow of a leakage stream, wherein the flow of the leakage stream through the second holes is greater than the flow of the leakage stream through the first holes.

[0072] In an implementation, one first hole of the plurality of holes in the first baffle is aligned with a corresponding one second hole of the plurality of holes in the second baffle.

[0073] In an implementation, a clearance between the plurality of tubes and the first holes is less than a clearance between the plurality of tubes and the second holes.

[0074] In an implementation, a clearance between the plurality of tubes and the first holes is configured to define a first leakage stream and a clearance between the plurality of tubes and the second holes is configured to define a second leakage stream having a flow volume greater than the first leakage stream.

[0075] In an implementation, the plurality of tubes are mechanically supported by the plurality of holes only in every other baffle.

[0076] In an implementation, a span of the plurality of tubes between support points on the plurality of baffles is less than a TEMA® standard span for the plurality of tubes.

[0077] In an implementation, a distance between successive first baffles of the plurality of helical baffles is less than a TEMA® standard span for the plurality of tubes.

[0078] In one or more implementations, a heat exchanger may be summarized as including: a shell; a plurality of baffles inside the shell; a plurality of holes in the plurality of baffles; a plurality of tubes received in the plurality of holes in the plurality of baffles; a first clearance between each of first holes of the plurality of holes and corresponding ones of the plurality of tubes; and a second clearance between each of second holes of the plurality of holes and corresponding ones of the plurality of tubes, wherein the second clearances are greater than the first clearances and configured to increase a leakage stream through the second clearances relative to the leakage stream through the first clearances.

[0079] In an implementation, the second clearance is at least two times greater than the first clearance.

[0080] In an implementation, the first clearance is a TEMA® standard clearance for a shell and tube heat exchanger with segmented or helical baffles.

[0081] In an implementation, the first holes have a first diameter and the second holes have a second diameter, the second diameter being greater than the first diameter.

[0082] In an implementation, the plurality of baffles are a plurality of helical baffles arranged in an alternating pattern of first baffles and second baffles.

[0083] In an implementation, each of the first baffles and the second baffles include first holes and second holes of the plurality of holes, the first holes and second holes of the first baffles arranged in an inverse pattern to the first holes and second holes of the second baffles.

[0084] In an implementation, the plurality of tubes are mechanically supported at the first holes in every other baffle of the plurality of baffles.

[0085] In an implementation, a distance between successive baffles of the plurality of baffles is less than a TEMA® standard span for the plurality of tubes.

[0086] In an implementation, the first holes and the second holes are arranged in an alternating pattern on the plurality of baffles.

[0087] In an implementation, the plurality of baffles includes first baffles with a first alternating pattern of first holes and second holes and second baffles with a second alternating pattern of first holes and second holes that is opposite to the first alternating pattern.

[0088] In one or more implementations, a method may be summarized as including: flowing a fluid through a shell of a heat exchanger, including flowing the fluid in a helical pattern via helical baffles in the shell of the heat exchanger; generating a first leakage stream by flowing the fluid through first clearances between first holes in the helical baffles and a plurality of tubes received in the first holes; and generating a second leakage stream greater than the first leakage stream based on total volume of flow by flowing the fluid through second clearances between second holes in the helical baffles and the plurality of tubes that are greater than the first clearances.

[0089] In an implementation, flowing the fluid in the helical pattern via the helical baffles includes flowing the fluid in the helical pattern across alternating first baffles and second baffles of the helical baffles.

[0090] In an implementation, each of the first baffles and each of the second baffles include first holes and second holes.

[0091] In an implementation, the method further includes, before flowing the fluid through the shell of the heat exchanger: coupling the plurality of tubes to the helical baffles with the plurality of tubes received in the first holes or the second holes, including supporting the plurality of tubes with the first holes in every other helical baffle.

[0092] In an implementation, an intervening baffle between the every other helical baffle includes a second hole corresponding to the first holes in the every other helical baffles.

[0093] In an implementation, generating the second leakage stream greater than the first leakage stream includes lowering a pressure drop across the heat exchanger relative to a comparative heat exchanger with only the first holes in all the baffles.

[0094] In an implementation, generating the second leakage stream includes maintaining a substantially constant rate of heat transfer relative to the comparative heat exchanger despite lowering the pressure drop.

[0095] In an implementation, a diameter of the first holes is less than a diameter of the second holes.

[0096] In one or more implementations, a heat exchanger may be summarized as including: a shell; a plurality of baffles inside the shell; a plurality of first holes in the plurality of baffles; a plurality of tubes received in the plurality of first holes in the plurality of baffles; and a plurality of second holes in the plurality of baffles between at least some of the plurality of first holes.

[0097] In an implementation, the plurality of first holes have a diameter greater than a diameter of the plurality of second holes.

[0098] In an implementation, the plurality of second holes are between all of the plurality of first holes.

[0099] In an implementation, a clearance between the plurality of tubes and the plurality of first holes is 1/32 inch.

[0100] The above description of illustrated implementations, including what is described in the Abstract, is not intended to be exhaustive or to limit the implementations to the precise forms disclosed. Although specific implementations and examples are described herein for illustrative purposes, various equivalent modifications can be made without departing from the spirit and scope of the disclosure, as will be recognized by those skilled in the relevant art. The teachings provided herein of the various implementations can be applied outside of the induction heating context, and are not limited to the example induction heating systems, methods, and devices generally described above.

[0101] Many of the methods described herein can be performed with variations. For example, many of the methods may include additional acts, omit some acts, and/or perform acts in a different order than as illustrated or described.

[0102] In the above description, certain specific details are set forth in order to provide a thorough understanding of various implementations of the disclosure. However, one skilled in the art will understand that the disclosure may be practiced without these specific details. In other instances, well-known structures associated with induction heating devices, systems, and methods have not been described in detail to avoid unnecessarily obscuring the descriptions of the implementations of the present disclosure.

[0103] Certain words and phrases used in the specification are set forth as follows. As used throughout this document, including the claims, the singular form “a”, “an”, and “the” include plural references unless indicated otherwise. Any of the features and elements described herein may be singular, *e.g.*, a shell may refer to one shell. The terms “include” and “comprise,” as well as derivatives thereof, mean inclusion without limitation. The phrases “associated with” and “associated therewith,” as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, or the like. Other definitions of certain words and phrases are provided throughout this disclosure.

[0104] The use of ordinals such as first, second, third, etc., does not necessarily imply a ranked sense of order, but rather may only distinguish between multiple instances of an act or a similar structure or material.

[0105] Throughout the specification, claims, and drawings, the following terms take the meaning explicitly associated herein, unless the context clearly dictates otherwise. The term “herein” refers to the specification, claims, and drawings associated with the current application. The phrases “in one implementation,” “in another implementation,” “in various implementations,” “in some implementations,” “in other implementations,” and other derivatives thereof refer to one or more features, structures, functions, limitations, or characteristics of the present disclosure, and are not limited to the same or different implementations unless the context clearly dictates otherwise. As used herein, the term “or” is an inclusive “or” operator, and is equivalent to the phrases “A or B, or both” or “A or B or C, or any combination thereof,” and lists with additional elements are similarly treated.

[0106] Generally, unless otherwise indicated, the materials for making the invention and/or its components may be selected from appropriate materials such as composite materials, ceramics, plastics, metal, polymers, thermoplastics, elastomers, plastic compounds, and the like, either alone or in any combination.

[0107] The foregoing description, for purposes of explanation, uses specific nomenclature and formula to provide a thorough understanding of the disclosed implementations. It should be apparent to those of skill in the art that the specific details are not required in order to practice the invention. The implementations have been chosen and described to best explain the principles of the disclosed implementations and its practical application, thereby enabling others of skill in the art to utilize the disclosed implementations, and various implementations with various modifications as are suited to the particular use contemplated. Thus, the foregoing disclosure is not intended to be exhaustive or to limit the invention to the precise forms disclosed, and those of skill in the art recognize that many modifications and variations are possible in view of the above teachings.

[0108] The terms “top,” “bottom,” “upper,” “lower,” “up,” “down,” “above,” “below,” “left,” “right,” and other like derivatives take their common meaning as directions or positional indicators, such as, for example, gravity pulls objects down and left refers to a direction that is to the west when facing north in a Cardinal direction scheme. These terms are not limiting with respect to the possible orientations explicitly disclosed, implicitly disclosed, or inherently

disclosed in the present disclosure and unless the context clearly dictates otherwise, any of the aspects of the implementations of the disclosure can be arranged in any orientation.

[0109] As used herein, the term “substantially” is construed to include an ordinary error range or manufacturing tolerance due to slight differences and variations in manufacturing. Unless the context clearly dictates otherwise, relative terms such as “approximately,” “substantially,” and other derivatives, when used to describe a value, amount, quantity, or dimension, generally refer to a value, amount, quantity, or dimension that is within plus or minus 5% of the stated value, amount, quantity, or dimension. It is to be further understood that any specific dimensions of components or features provided herein are for illustrative purposes only with reference to the various implementations described herein, and as such, it is expressly contemplated in the present disclosure to include dimensions that are more or less than the dimensions stated, unless the context clearly dictates otherwise.

[0110] The present application claims priority to U.S. Provisional Patent Application No. 63/596,526 filed on November 6, 2023, the entire contents of which are incorporated herein by reference.

[0111] These and other changes can be made to the implementations in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific implementations disclosed in the specification and the claims, but should be construed to include all possible implementations along with the full scope of equivalents to which such claims are entitled. Accordingly, the breadth and scope of a disclosed implementation should not be limited by any of the above-described implementations, but should be defined only in accordance with the following claims and their equivalents.

CLAIMS

1. A heat exchanger, comprising:
a shell having a longitudinal axis;
a plurality of helical baffles inside the shell and arranged along the longitudinal axis in an alternating pattern of a first baffle followed by a second baffle of the plurality of helical baffles;
a plurality of holes in the plurality of helical baffles, the plurality of holes including first holes having a first diameter and second holes having a second diameter greater than the first diameter; and
a plurality of tubes received in the plurality of holes in the plurality of baffles.
2. The heat exchanger of claim 1, wherein a clearance between the plurality of tubes and the first holes is approximately 1/32 inch.
3. The heat exchanger of claim 2, wherein a clearance between the plurality of tubes and the second holes is greater than 1/32 inch.
4. The heat exchanger of claim 2, wherein a clearance between the plurality of tubes and the second holes is at least 1/16 inch.
5. The heat exchanger of claim 1, wherein the first holes in the first baffle are aligned with the second holes in the second baffle.
6. The heat exchanger of claim 5, wherein the second holes in the first baffle are aligned with the first holes in the second baffle.
7. The heat exchanger of claim 1, wherein the first holes and the second holes of the plurality of helical baffles are arranged in an alternating pattern.
8. The heat exchanger of claim 1, wherein a baffle overlap between successive baffles of the plurality of helical baffles is at least 40%.

9. The heat exchanger of claim 1, wherein the plurality of holes includes an outermost series of holes in the plurality of helical baffles each having a same diameter.
10. The heat exchanger of claim 1, wherein the plurality of helical baffles are arranged at an angle to a plane normal to the longitudinal axis between 5 degrees and 45 degrees.
11. The heat exchanger of claim 1, wherein the plurality of holes are round holes, square or quadrangular holes, hexagonal cinquefoil holes, trefoil holes, or reticulated holes.
12. The heat exchanger of claim 1, wherein the shell and the plurality of helical baffles are configured to assist, at least in part, in defining a main flow path through the shell and a clearance between the plurality of holes and the plurality of tubes is configured to define a flow of a leakage stream, wherein the flow of the leakage stream through the second holes is greater than the flow of the leakage stream through the first holes.
13. The heat exchanger of claim 1, wherein one first hole of the plurality of holes in the first baffle is aligned with a corresponding one second hole of the plurality of holes in the second baffle.
14. The heat exchanger of claim 1, wherein a clearance between the plurality of tubes and the first holes is less than a clearance between the plurality of tubes and the second holes.
15. The heat exchanger of claim 1, wherein a clearance between the plurality of tubes and the first holes is configured to define a first leakage stream and a clearance between the plurality of tubes and the second holes is configured to define a second leakage stream having a flow volume greater than the first leakage stream.
16. The heat exchanger of claim 1, wherein the plurality of tubes are mechanically supported by the plurality of holes only in every other baffle.
17. The heat exchanger of claim 1, wherein a span of the plurality of tubes between support points on the plurality of baffles is less than a TEMA® standard span for the plurality of tubes.

18. The heat exchanger of claim 1, wherein a distance between successive first baffles of the plurality of helical baffles is less than a TEMA® standard span for the plurality of tubes.

19. A heat exchanger, comprising:
a shell;
a plurality of baffles inside the shell;
a plurality of holes in the plurality of baffles;
a plurality of tubes received in the plurality of holes in the plurality of baffles;
a first clearance between each of first holes of the plurality of holes and corresponding ones of the plurality of tubes; and
a second clearance between each of second holes of the plurality of holes and corresponding ones of the plurality of tubes, wherein the second clearances are greater than the first clearances and configured to increase a leakage stream through the second clearances relative to the leakage stream through the first clearances.

20. The heat exchanger of claim 19, wherein the second clearance is at least two times greater than the first clearance.

21. The heat exchanger of claim 20, wherein the first clearance is a TEMA® standard clearance for a shell and tube heat exchanger with segmented or helical baffles.

22. The heat exchanger of claim 19, wherein the first holes have a first diameter and the second holes have a second diameter, the second diameter being greater than the first diameter.

23. The heat exchanger of claim 19, wherein the plurality of baffles are a plurality of helical baffles arranged in an alternating pattern of first baffles and second baffles.

24. The heat exchanger of claim 23, wherein each of the first baffles and the second baffles include first holes and second holes of the plurality of holes, the first holes and second holes of the first baffles arranged in an inverse pattern to the first holes and second holes of the second baffles.

25. The heat exchanger of claim 19, wherein the plurality of tubes are mechanically supported at the first holes in every other baffle of the plurality of baffles.

26. The heat exchanger of claim 19, wherein a distance between successive baffles of the plurality of baffles is less than a TEMA® standard span for the plurality of tubes.

27. The heat exchanger of claim 19, wherein the first holes and the second holes are arranged in an alternating pattern on the plurality of baffles.

28. The heat exchanger of claim 19, wherein the plurality of baffles includes first baffles with a first alternating pattern of first holes and second holes and second baffles with a second alternating pattern of first holes and second holes that is opposite to the first alternating pattern.

29. A method, comprising:
flowing a fluid through a shell of a heat exchanger, including flowing the fluid in a helical pattern via helical baffles in the shell of the heat exchanger;
generating a first leakage stream by flowing the fluid through first clearances between first holes in the helical baffles and a plurality of tubes received in the first holes; and
generating a second leakage stream greater than the first leakage stream based on total volume of flow by flowing the fluid through second clearances between second holes in the helical baffles and the plurality of tubes that are greater than the first clearances.

30. The method of claim 29, wherein flowing the fluid in the helical pattern via the helical baffles includes flowing the fluid in the helical pattern across alternating first baffles and second baffles of the helical baffles.

31. The method of claim 30, wherein each of the first baffles and each of the second baffles include first holes and second holes.

32. The method of claim 29, further comprising, before flowing the fluid through the shell of the heat exchanger:

coupling the plurality of tubes to the helical baffles with the plurality of tubes received in the first holes or the second holes, including supporting the plurality of tubes with the first holes in every other helical baffle.

33. The method of claim 32, wherein an intervening baffle between the every other helical baffle includes a second hole corresponding to the first holes in the every other helical baffles.

34. The method of claim 29, wherein generating the second leakage stream greater than the first leakage stream includes lowering a pressure drop across the heat exchanger relative to a comparative heat exchanger with only the first holes in all the baffles.

35. The method of claim 34, wherein generating the second leakage stream includes maintaining a substantially constant rate of heat transfer relative to the comparative heat exchanger despite lowering the pressure drop.

36. The method of claim 29, wherein a diameter of the first holes is less than a diameter of the second holes.

37. A heat exchanger, comprising:
a shell;
a plurality of baffles inside the shell;
a plurality of first holes in the plurality of baffles;
a plurality of tubes received in the plurality of first holes in the plurality of baffles; and
a plurality of second holes in the plurality of baffles between at least some of the plurality of first holes.

38. The heat exchanger of claim 37, wherein the plurality of first holes have a diameter greater than a diameter of the plurality of second holes.

39. The heat exchanger of claim 37, wherein the plurality of second holes are between all of the plurality of first holes.

40. The heat exchanger of claim 37, wherein a clearance between the plurality of tubes and the plurality of first holes is 1/32 inch.