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(54) **HEAT EXCHANGER**

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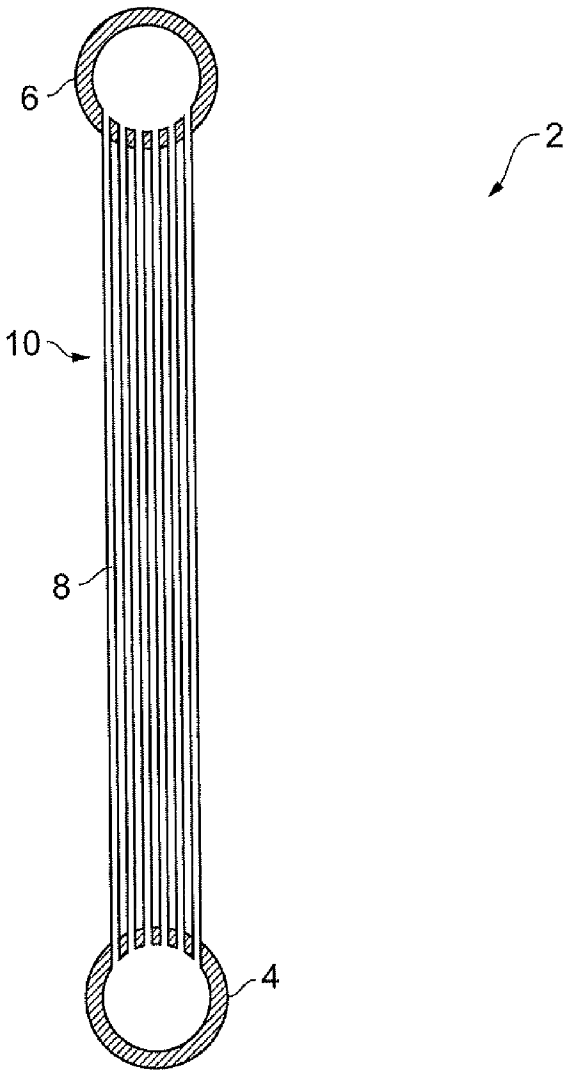
(52) **U.S. Cl.**

CPC .... *F28F 9/02* (2013.01); *F28F 1/00* (2013.01)

USPC ........................................................ **165/173**

(57) **ABSTRACT**

A heat exchanger **302** comprising: an inlet manifold **304**; an outlet manifold **306**; and a tube matrix **310** comprising a plurality of tubes **308**, each tube **308** being connected at one end to the inlet manifold **304** and at the other end to the outlet manifold **306**; wherein each tube extends generally along a longitudinal axis defined between the connection of the tube **308** with the inlet manifold **304** and the connection of the tube **308** with the outlet manifold **306**; and wherein a single portion **314** of each tube **308** is offset to one side of the longitudinal axis.



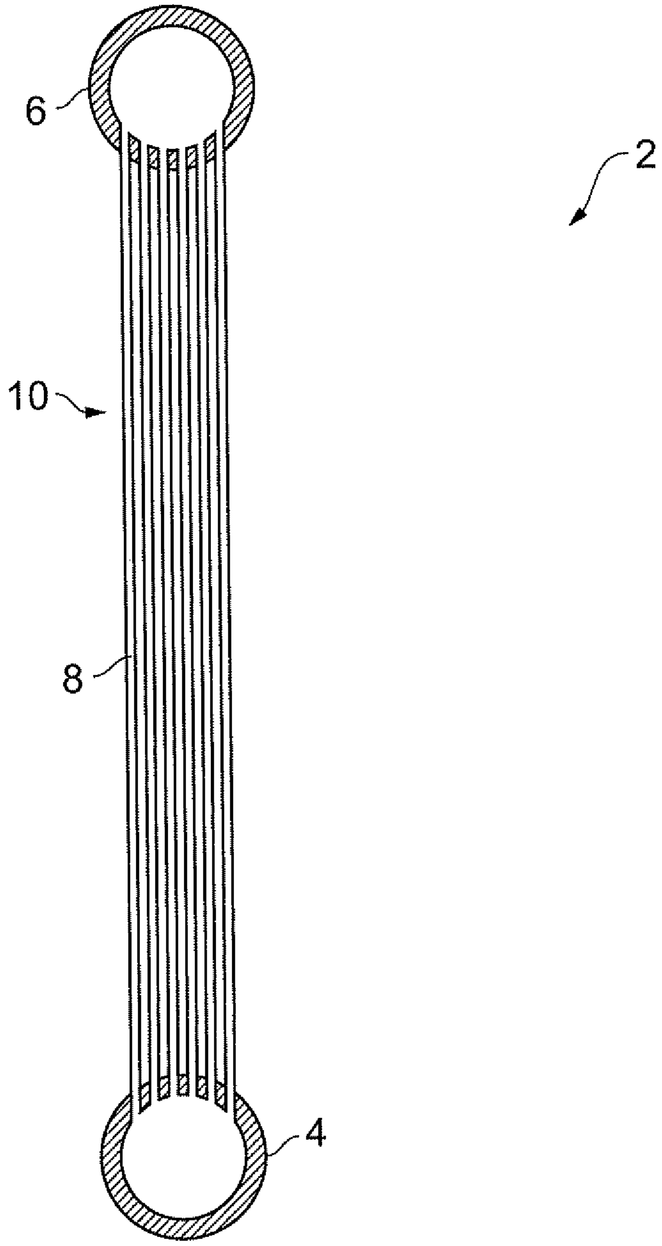


FIG. 1

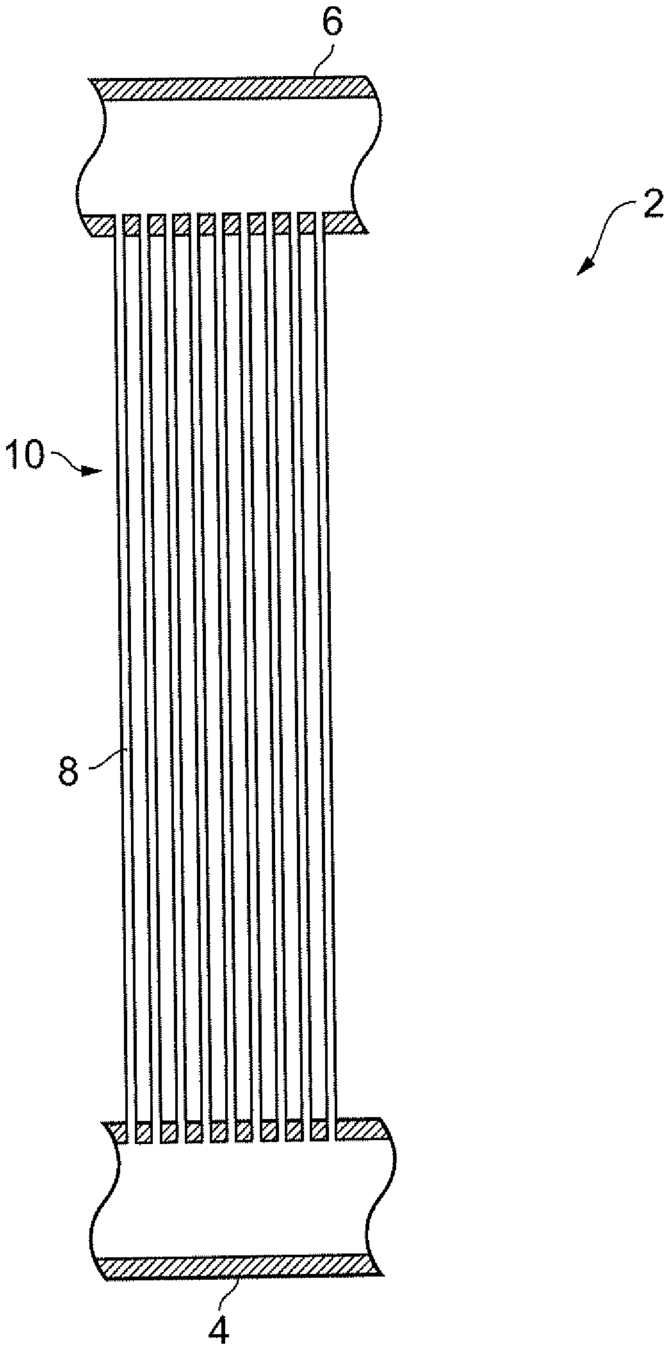
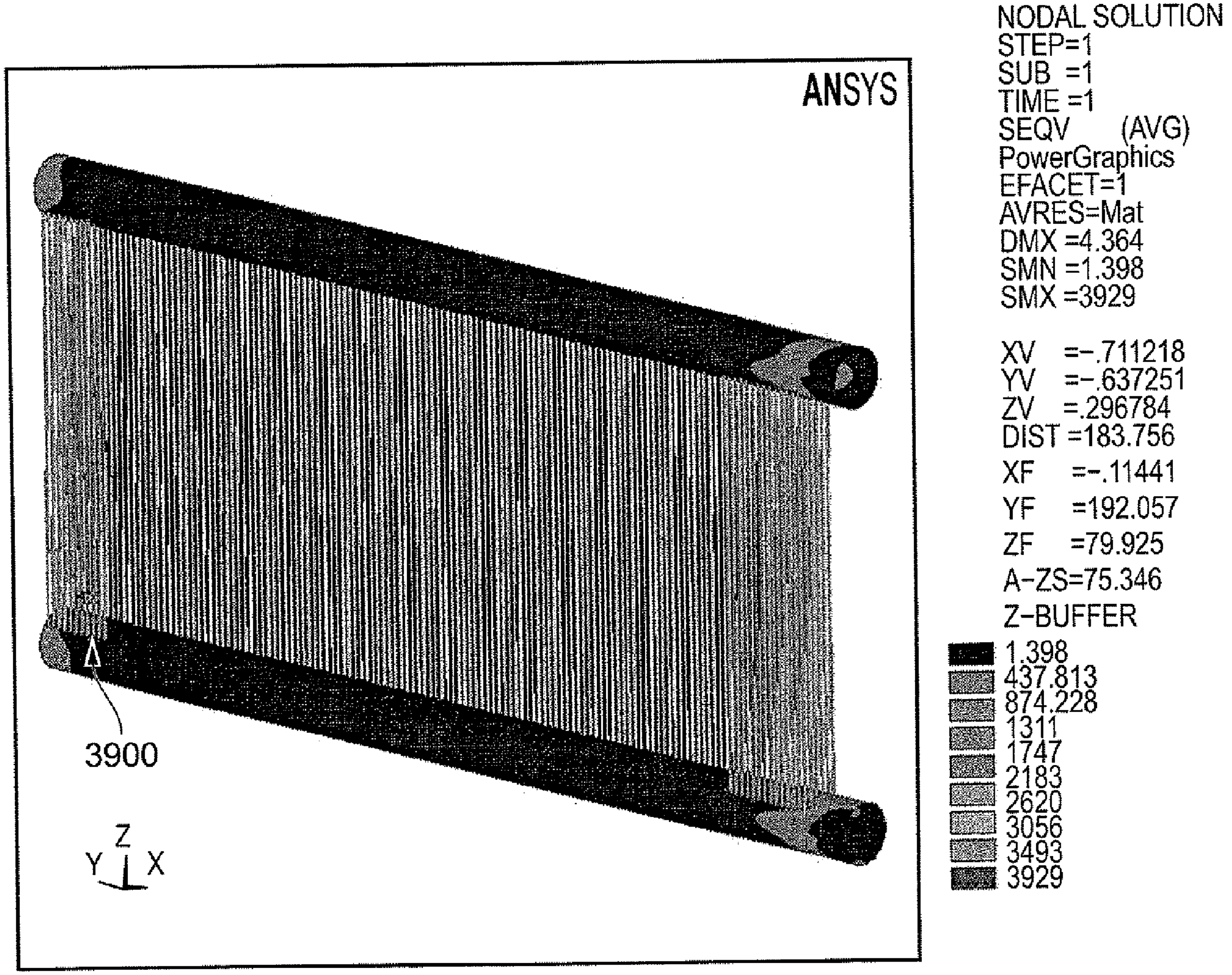


FIG. 2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XF =-.11441
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ZF =79.925
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2620
3056
3493
3929

FIG. 3

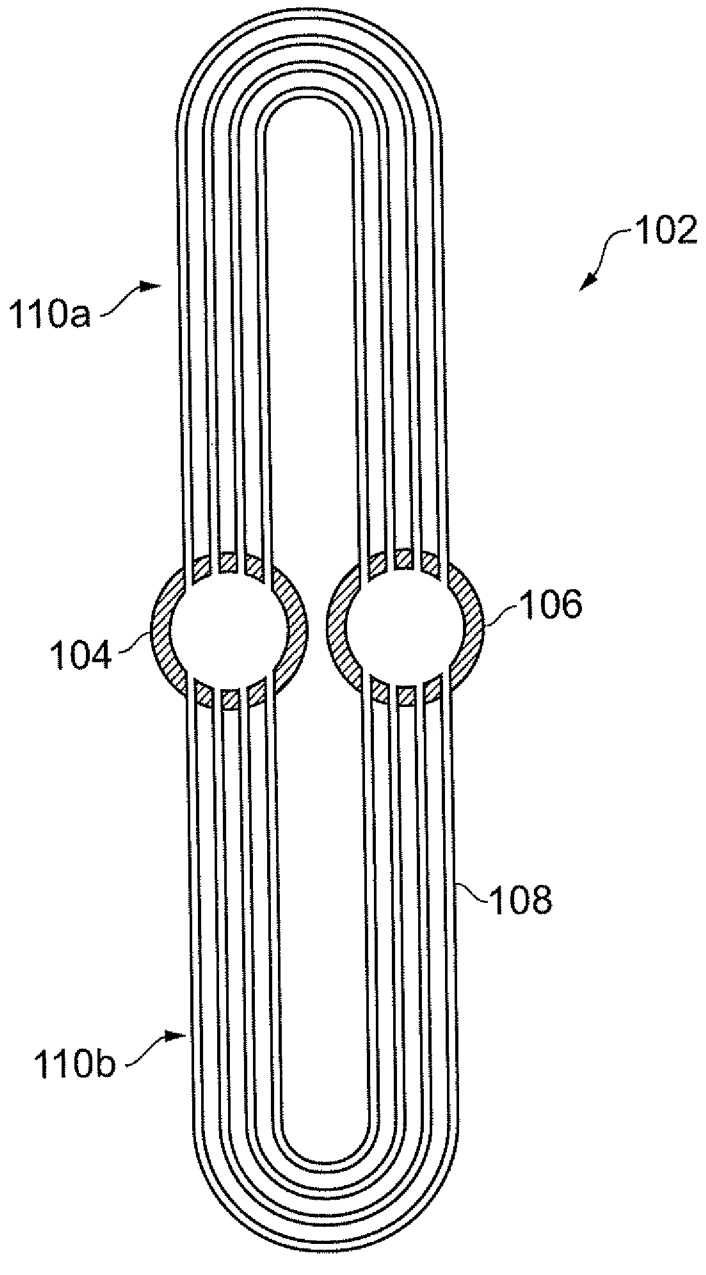


FIG. 4

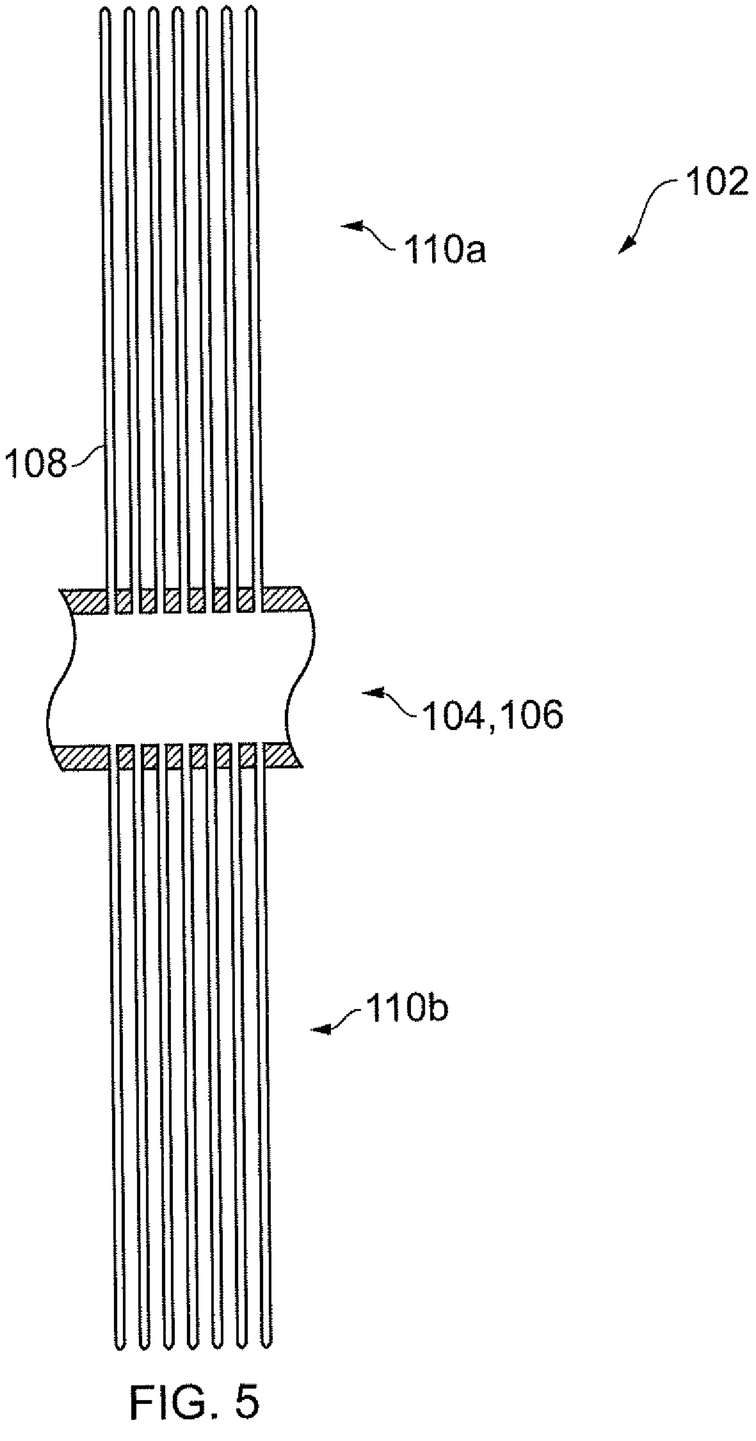
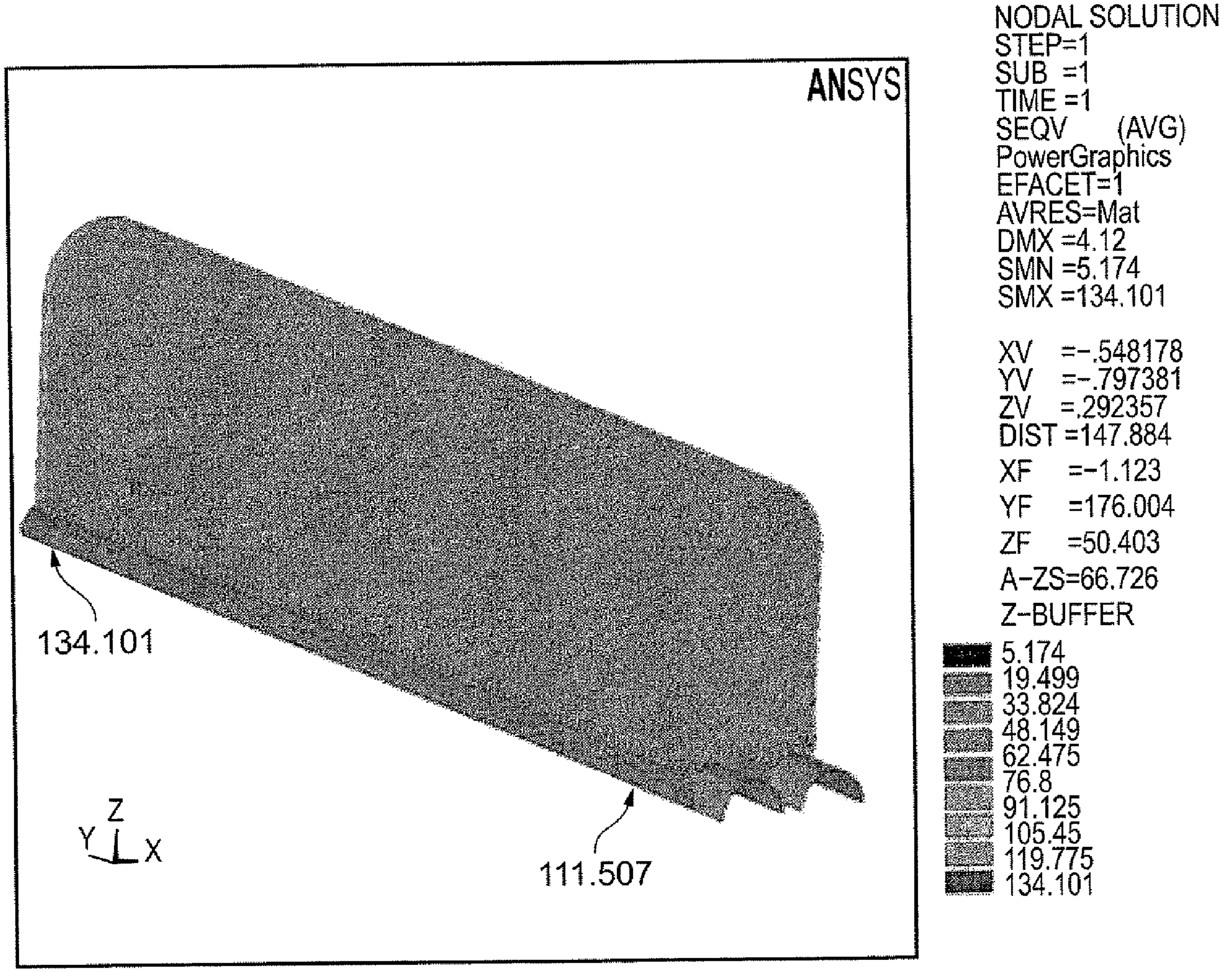


FIG. 5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33.824
48.149
62.475
76.8
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105.45
119.775
134.101

FIG. 6

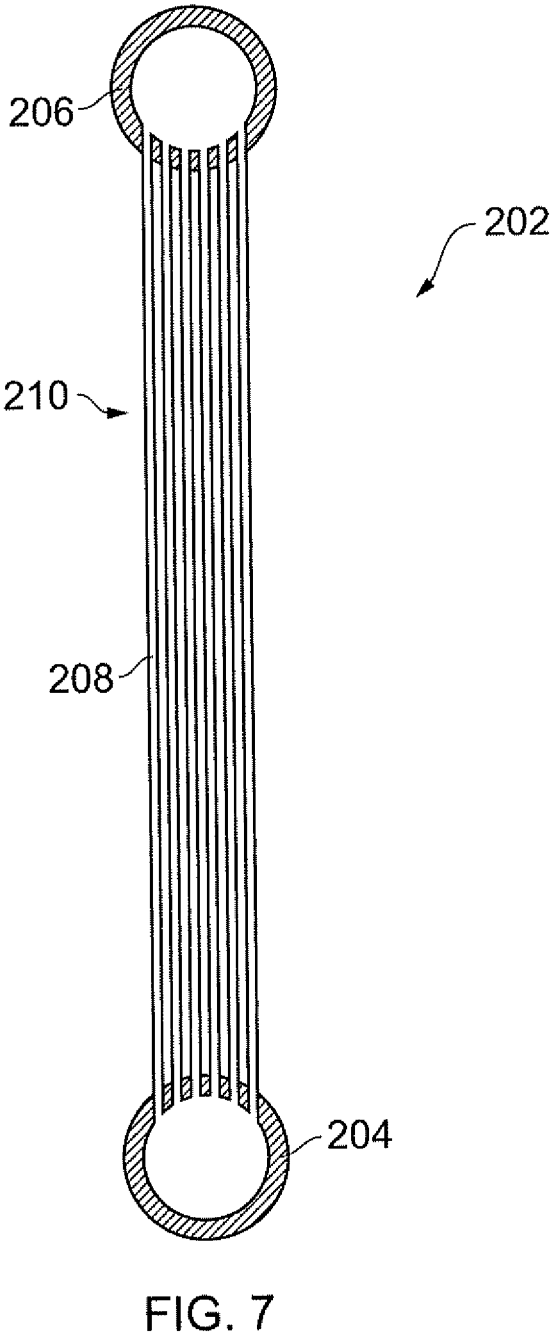


FIG. 7

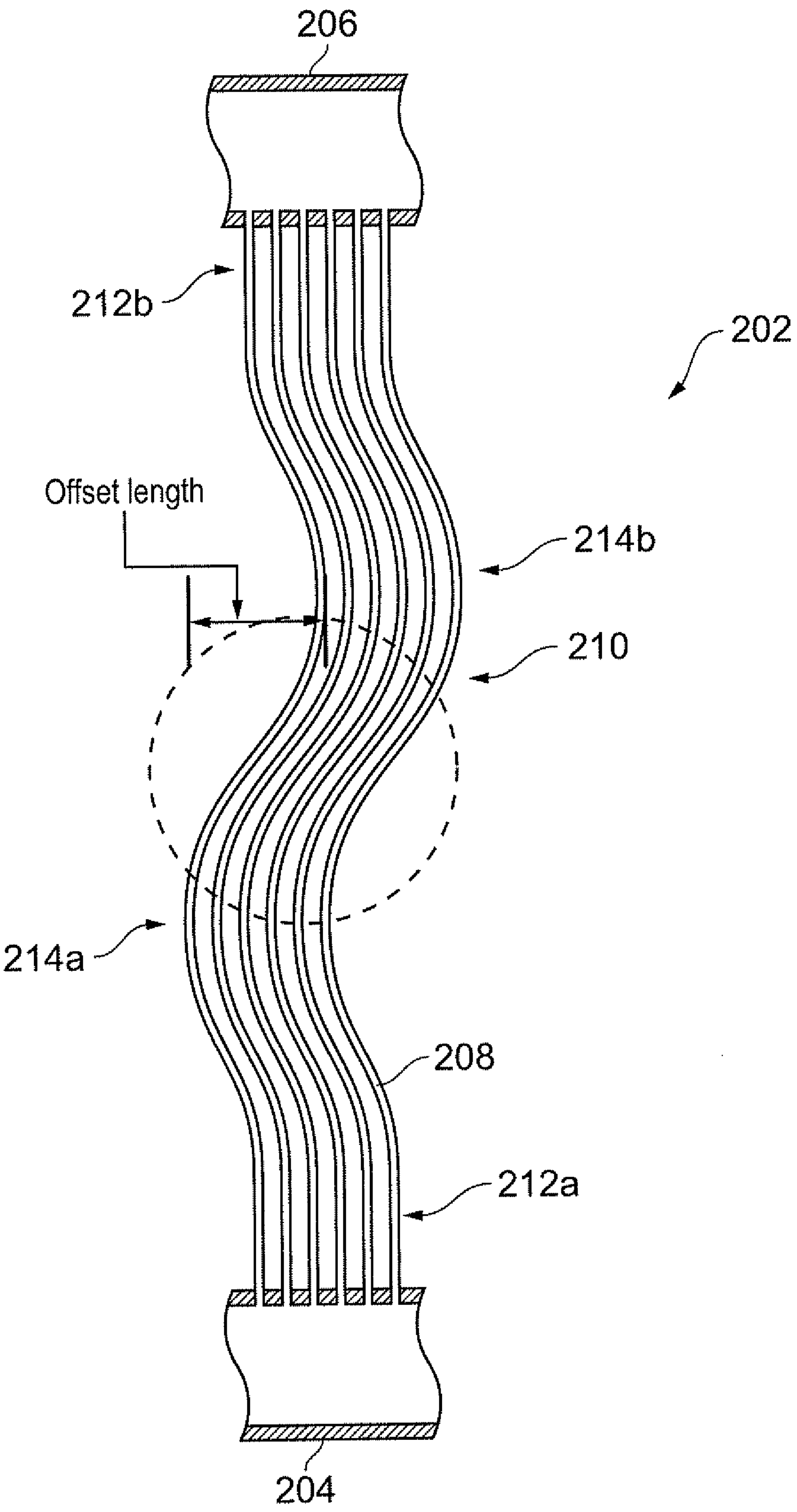


FIG. 8

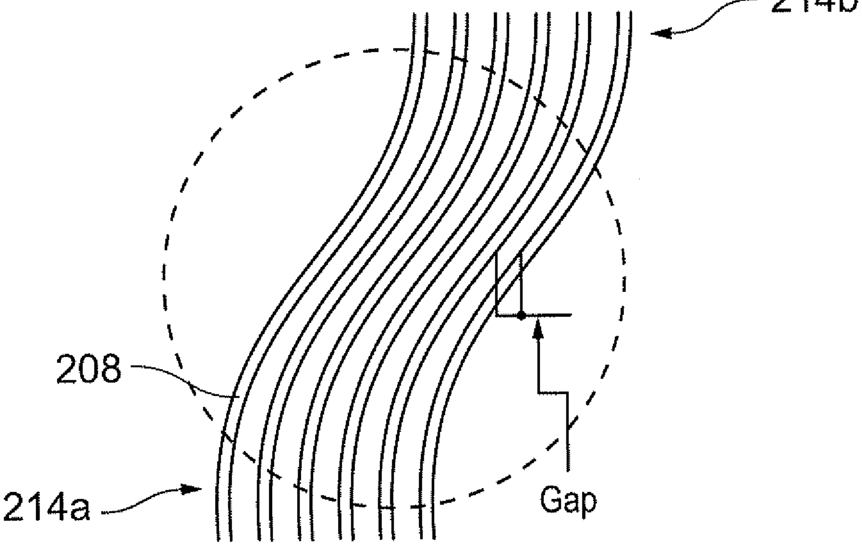


FIG. 9

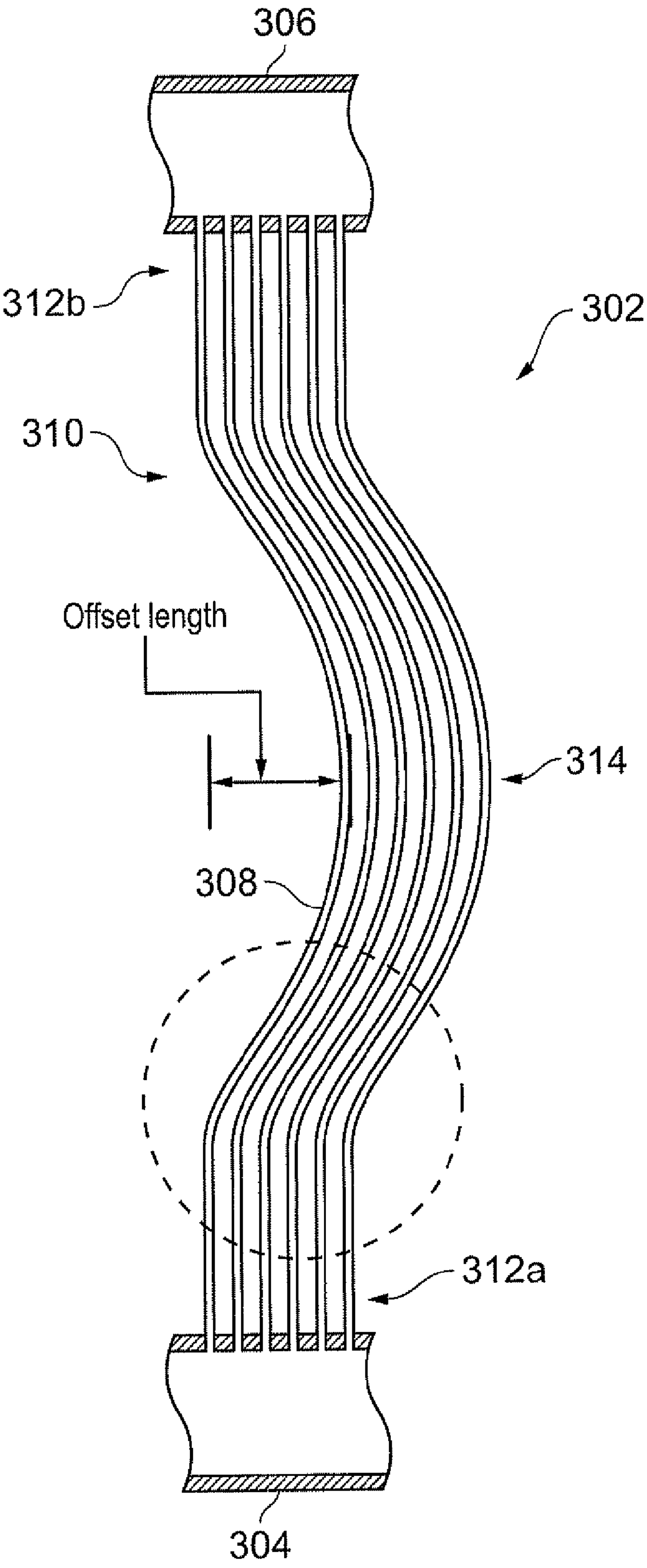


FIG. 10

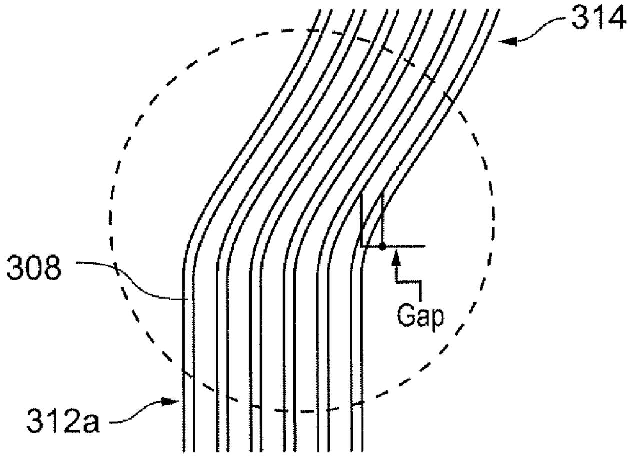
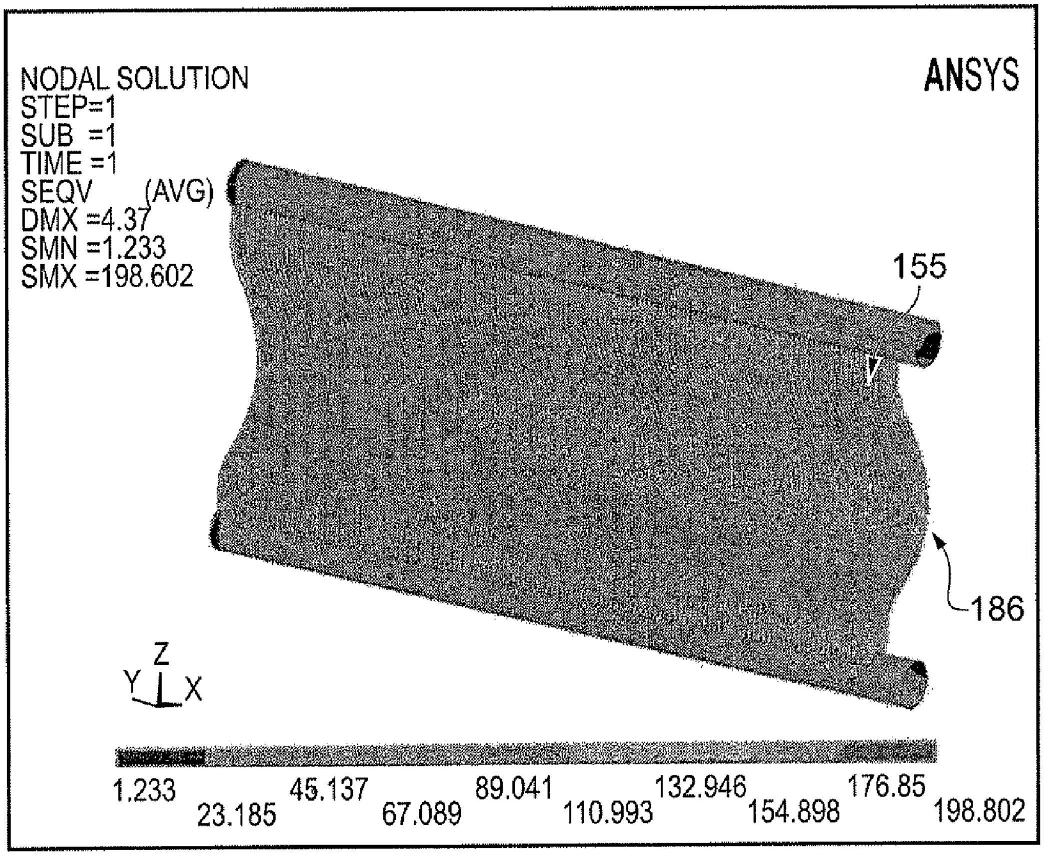

314
308
Gap
312a

FIG. 11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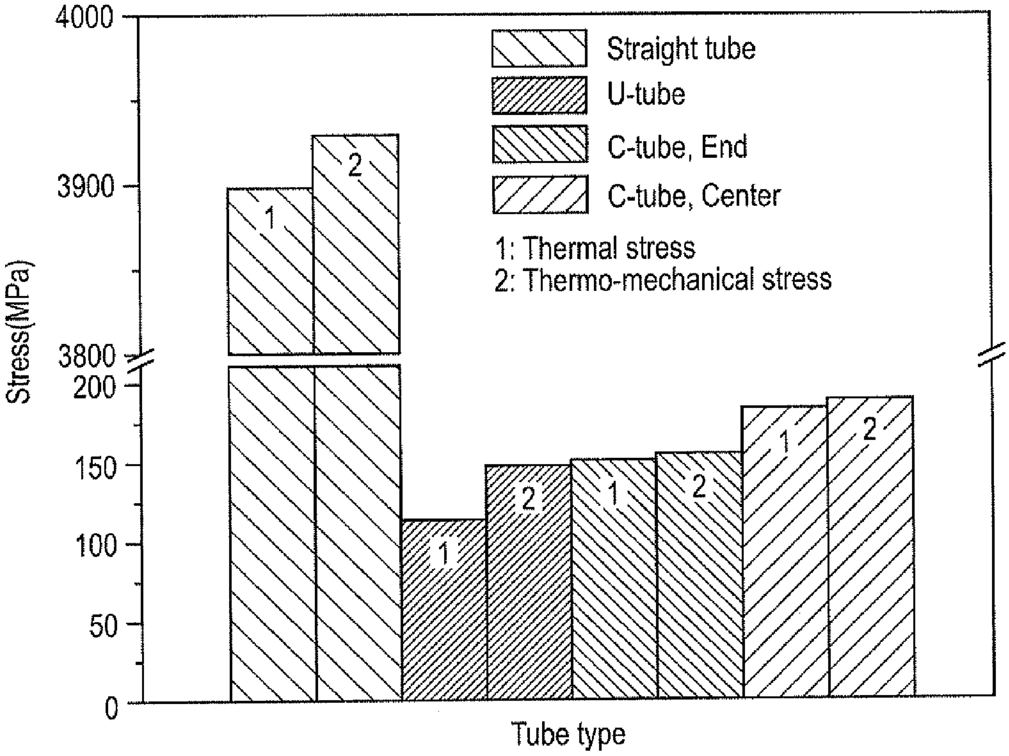
198.802

FIG. 12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3800
200
150
100
50
0
Stress(MPa)
Tube type
Straight tube
U-tube
C-tube, End
C-tube, Center
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2: Thermo-mechanical stress
1
2
1
2
1
2
1
2

FIG. 13

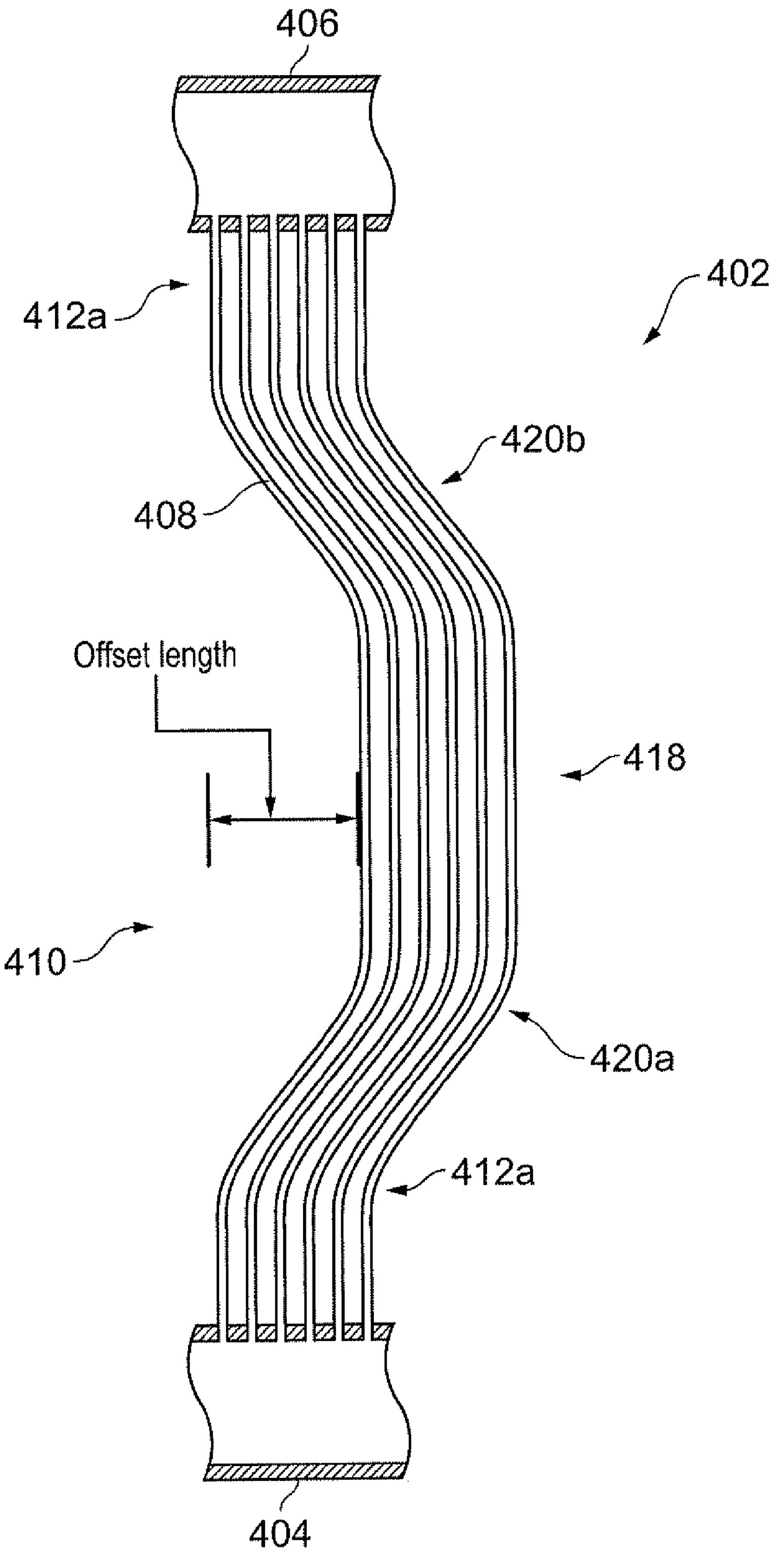

FIG. 14

# HEAT EXCHANGER

**[0001]** The present invention relates to a heat exchanger, and particularly but not exclusively to a heat exchanger having a tube matrix which reduces thermal stress experienced by the heat exchanger.

**[0002]** Heat exchangers are widely used to transfer heat from a relatively hot fluid to a relatively cold fluid without direct contact between the fluids.

**[0003]** A conventional tube heat exchanger is shown in FIGS. **1** and **2**. The heat exchanger **2** comprises an inlet manifold **4** and an outlet manifold **6**. The inlet and outlet manifolds **4**, **6** are fluidically coupled by a plurality of tubes **8** which together form a tube matrix **10**. The tubes **8** of the tube matrix **10** are coupled at one end to the inlet manifold **4** and are coupled at the other end to the outlet manifold **6**.

**[0004]** The tubes **8** of the tube matrix **10** are arranged such that their longitudinal axes are perpendicular to the longitudinal axes of the inlet and outlet manifolds **4**, **6**. A plurality of the tubes **8** are aligned in a plane of the longitudinal axes of the inlet and outlet manifolds **4**, **6** to form a row, and several rows are disposed side-by-side to form columns of the tube matrix **10**.

**[0005]** As shown in FIGS. **1** and **2**, the tubes **8** of the tube matrix **10** are straight. Each tube **8** therefore follows a direct path from the inlet manifold **4** to the outlet manifold **6** without deviating from a longitudinal axis between its connection point with the inlet manifold **4** and its connection point with the outlet manifold **6**.

**[0006]** The inlet and outlet manifolds **4**, **6** and tube matrix **10** form a conduit for the passage of a first fluid through the heat exchanger **2**. Accordingly, the first fluid flows into the heat exchanger **2** via the inlet manifold **4**, passes through the tubes **8** of the tube matrix **10** and exits the heat exchanger **2** via the outlet manifold **6**.

**[0007]** A second fluid flows over exterior surfaces of the tubes **8** of the tube matrix **10**. The first and second fluids have different temperatures and therefore heat is transferred between the first and second fluids.

**[0008]** FIG. **3** shows a simulated stress distribution for the heat exchanger **2** under large thermal and pressure loads. In this simulation, the ends of the inlet and outlet manifolds **4**, **6** are assumed to have a fixed position.

**[0009]** As shown in FIG. **3**, the heat exchanger **2** experiences large stresses throughout as a result of thermal expansion of the inlet and outlet manifolds **4**, **6** and the tubes **8** of the tube matrix **10**. Increased loads are seen across those tubes **8** which are located towards the ends of the inlet and outlet manifolds **4**, **6** due to the fixed position of the inlet and outlet manifolds **4**, **6** at these locations.

**[0010]** Various tube matrix geometries have been proposed to reduce the stress experienced by heat exchangers under large thermal and pressure loads.

**[0011]** For example, FIGS. **4** and **5** show a heat exchanger **102** which has a tube matrix **110** which is formed of two portions **110*a***, **110*b*** comprising U-shaped tubes **108**. Each U-shaped portion **110*a***, **110*b*** is connected at one end to the inlet manifold **104** and at the other end to the outlet manifold **106**. The U-shaped portions **110*a***, **110*b*** extend in opposite directions from the inlet and outlet manifolds **104**, **106** to form an oval.

**[0012]** FIG. **6** shows a simulated stress distribution for the U-shaped heat exchanger **102** under large thermal and pressure loads. As can be seen, the stress levels are far reduced for the tube matrix **102**, since the U-shaped tubes **108** are not constrained by the inlet and outlet manifolds **104**, **106**. Accordingly, the U-shaped heat exchanger **102** is insensitive to the displacement constraints.

**[0013]** However, the U-shaped heat exchanger **102** requires more space and is heavier than the straight tube matrix **2**.

**[0014]** FIGS. **7** and **8** show another example of a known heat exchanger **202**. The heat exchanger **202** has an S-shaped tube matrix **210**, with the tubes **208** of the tube matrix **210** following a serpentine path between the inlet manifold **204** and the outlet manifold **206**.

**[0015]** Specifically, the tubes **208** of the S-shaped tube matrix **210** comprise first and second straight portions **212*a***, **212*b*** adjacent the inlet and outlet manifolds **204**, **206** respectively, and first and second curved portions **214*a***, **214*b*** disposed between the first and second straight portions **212*a***, **212*b***. The first and second curved portions **214*a***, **214*b*** deviate in opposite directions from the axis of the first and second straight portions **212*a***, **212*b*** in a plane defined by the longitudinal axes of the inlet and outlet manifolds **204**, **206** to form the S-shape.

**[0016]** The S-shaped nature of the tube matrix **210** acts to reduce the thermal stress placed on the heat exchanger **202**, without considerably increasing the size and weight of the heat exchanger.

**[0017]** However, as shown in FIG. **9**, the gap between adjacent tubes **208** is reduced over the first and second curved portions **214*a***, **214*b*** of the S-shaped tube matrix **210**. Consequently, the tubes **208** must be spaced further from one another at the inlet and outlet manifolds **204**, **206** in order to prevent the tubes **208** from contacting one another. This reduces the number of tubes **208** in the tube matrix **210** for a fixed size heat exchanger **202** or increases the size of the heat exchanger **202** for a fixed number of tubes **208**. Furthermore, the curved portions **214*a***, **214*b*** increase the complexity of the manufacturing process, thus increasing the cost of the heat exchanger.

**[0018]** Further tube matrix geometries are known which use tubes with additional curved portions; for example, see U.S. Pat. No. 5,058,663. However, although these matrices may reduce thermal stress, they exacerbate the reduction in the gap between the tubes and the increased complexity and cost of manufacturing.

**[0019]** Accordingly, it is desirable to provide a heat exchanger with a tube matrix which overcomes some or all of the problems described above.

**[0020]** In accordance with a first aspect of the invention there is provided a heat exchanger comprising: an inlet manifold; an outlet manifold; and a tube matrix comprising a plurality of tubes, each tube being fixedly connected at one end to the inlet manifold and at the other end to the outlet manifold; wherein each tube extends generally along a longitudinal axis defined between the connection of the tube with the inlet manifold and the connection of the tube with the outlet manifold; and wherein a single portion of each tube is offset to one side of the longitudinal axis.

**[0021]** The tubes may be fixedly connected between the inlet manifold and outlet manifold independently from each other.

**[0022]** The tubes may each be separated from an adjacent tube by a substantially similar gap at corresponding portions along the longitudinal axis.

**[0023]** The tubes may be generally C-shaped.

**[0024]** The offset portion may comprise a curved portion which curves away from the longitudinal axis.

**[0025]** The curved portion may have a constant curvature.

**[0026]** The offset portion may comprise a straight portion and pair of angled portions which offset the straight portion from the longitudinal axis.

**[0027]** The offset portion may be offset in a plane defined by a longitudinal axis of the inlet and outlet manifolds.

**[0028]** The tubes may be arranged in one or more rows in a plane defined by a longitudinal axis of the inlet and outlet manifolds.

**[0029]** A plurality of rows may be disposed side-by-side to form columns.

**[0030]** A minimum gap between adjacent tubes over the offset portion may be greater than ⅔ of the maximum gap between adjacent tubes at the inlet and outlet manifolds.

**[0031]** The offset portion may be 30-70% of the total length of the tube.

**[0032]** The offset portion may allow deformation of the tubes during thermal expansion, thereby reducing thermal stress experienced by the heat exchanger. Furthermore, the offset portion does not considerably affect the gaps between adjacent tubes. Consequently, the size of the heat exchanger is not significantly increased, if at all. This may make the heat exchanger of the present invention particularly suitable for installation in an aero-engine, where space is at a premium.

**[0033]** In addition, the manufacturing process for the single offset portion is simple and requires only one bending process. Accordingly, the manufacturing costs are minimised.

**[0034]** The present invention results in a high efficiency, high temperature, high pressure, lightweight and compact heat exchanger design.

**[0035]** According to another aspect of the invention there is provided a heat exchanger comprising an inlet manifold, an outlet manifold, and a tube array comprising a plurality of tubes, wherein the tube array generally extends along a longitudinal axis between the inlet manifold and the outlet manifold, and wherein the tube array comprises an offset portion that is offset from the longitudinal axis. There may be a single offset portion. Each tube may comprise an offset portion that is offset to the same side. The tube array may comprise at least one longitudinally extending portion and an offset portion. The tube array may comprise first and second longitudinally extending portions coupled to the inlet and outlet manifolds respectively, with the offset portion disposed between the first and second longitudinally extending portions. The single offset portion may be directly between the first and second longitudinally extending portions. The offset portion may be generally C-shaped.

**[0036]** For a better understanding of the present invention, and to show more clearly how it may be carried into effect, reference will now be made by way of example to the accompanying drawings, in which:

**[0037]** FIG. **1** is a cross-sectional view of a conventional heat exchanger having a straight tube matrix in a plane defined by a longitudinal axis of the tubes;

**[0038]** FIG. **2** is a cross-sectional view of the heat exchanger of FIG. **1** in a plane defined by a longitudinal axis of the manifolds;

**[0039]** FIG. **3** is a simulated stress distribution for the heat exchanger of FIGS. **1** and **2**;

**[0040]** FIG. **4** is a cross-sectional view through a conventional heat exchanger having a U-shape tube matrix in a plane defined by a longitudinal axis of the tubes;

**[0041]** FIG. **5** is a cross-sectional view of the heat exchanger of FIG. **5** in a plane defined by a longitudinal axis of the manifolds;

**[0042]** FIG. **6** is a simulated stress distribution for the heat exchanger of FIGS. **4** and **5**;

**[0043]** FIG. **7** is a cross-sectional view through a conventional heat exchanger having a S-shaped matrix in a plane defined by a longitudinal axis of the tubes;

**[0044]** FIG. **8** is a cross-sectional view of the heat exchanger of FIG. **7** in a plane defined by a longitudinal axis of the manifolds;

**[0045]** FIG. **9** is an enlarged view of a portion of FIG. **8**;

**[0046]** FIG. **10** is a cross-sectional view through an embodiment of a heat exchanger in a plane defined by a longitudinal axis of the manifolds;

**[0047]** FIG. **11** is an enlarged view of a portion of FIG. **10**;

**[0048]** FIG. **12** is a simulated stress distribution for the heat exchanger of FIG. **11**;

**[0049]** FIG. **13** is a comparative graph of thermal and thermo-mechanical stress for conventional heat exchangers and the heat exchanger of the present invention; and

**[0050]** FIG. **14** is a cross-sectional view through another embodiment of a heat exchanger in a plane defined by a longitudinal axis of the manifolds.

## DETAILED DESCRIPTION

**[0051]** FIG. **10** shows a heat exchanger **302** according to an embodiment of the invention. The heat exchanger **302** comprises an inlet manifold **304** and an outlet manifold **306**. The inlet and outlet manifolds **304**, **306** are fluidically coupled by a plurality of tubes **308** which together form a tube matrix **310**. The tubes **308** of the tube matrix **310** are fixedly connected, for example, by welding, at one end to the inlet manifold **304** and are coupled at the other end to the outlet manifold **306**.

**[0052]** A plurality of the tubes **308** are aligned in a plane defined by the longitudinal axes of the inlet and outlet manifolds **304**, **306** to form a row, and several rows are disposed side-by-side to form columns of the tube matrix **310** arranged along a common plane.

**[0053]** Each tube **308** comprises first and second straight portions **312*a***, **312*b*** adjacent the inlet and outlet manifolds **304**, **306** respectively, and a single curved portion **314** disposed between the first and second straight portions **312*a***, **312*b***. The curved portion **314** deviates from a longitudinal axis of the tube **308** between its connection point with the inlet manifold **304** and its connection point with the outlet manifold **306**. As shown in FIG. **10**, the curved portion **314** is offset in the plane defined by the longitudinal axes of the inlet and outlet manifolds **304**, **306**. The size of the offset from this longitudinal axis is defined as the offset length. The curved portion **314** follows a single curvature between the first straight portion **312*a*** and the second straight portion **312*b***. Accordingly, the tube matrix **310** is generally C-shaped. Further, each of the tubes is separated from adjacent tubes by a similar gap at corresponding portions along the length of the tubes and are held between the manifolds independently of each other in the present embodiment, although supporting members may be incorporated between each of the tubes to help maintain a common gap therebetween.

**[0054]** The inlet and outlet manifolds **304**, **306** and tube matrix **310** form a conduit for the passage of a first fluid through the heat exchanger **302**. Accordingly, the first fluid flows into the heat exchanger **302** via the inlet manifold **304**, passes through the tubes **308** of the tube matrix **310** and exits the heat exchanger **302** via the outlet manifold **306**.

**[0055]** As shown in FIG. **11**, whilst the gap between adjacent tubes **308** is reduced over the curved portion **314**, the size of this reduction is minimised. Consequently, the spacing between the tubes **308** at the inlet and outlet manifolds **304**, **306** is not significantly effected.

**[0056]** The curved portion **314** absorbs thermal expansion by elastically deforming. Thus, the curved portion **314** reduces the thermal stress experienced by the heat exchanger **302**.

**[0057]** The geometry of the tube matrix **310** is optimised in order to minimise the thermal stress experienced by the heat exchanger **302**. Accordingly, a design of experiment (DOE) analysis was performed using the Central Composite Design method and sensitivity analysis and response surface analysis was performed using the results of the DOE analysis.

**[0058]** From the results of the sensitivity analysis it was shown that the offset length and the length of the straight portions **312***a*, **312***b* (straight length) were found to be the most significant factors in reducing the thermal stress.

**[0059]** The response surface analysis was performed in order to find the optimum values for the offset length, the straight length and the curvature of the curved portion **314** which minimise the thermal stress, whilst maintaining a minimum gap between adjacent tubes over the curved portion **314** of ⅔ the maximum gap at the inlet and outlet manifolds **304**, **306**.

**[0060]** The result of this process showed that the thermal stress at the ends of the heat exchanger **302** (i.e. adjacent the inlet and outlet manifolds **304**, **306**) decreases as the straight length and the offset length increase. Furthermore, the thermal stress at the centre of the heat exchanger **302** (i.e. midway between the inlet and outlet manifolds **304**, **306**) was shown to decrease with increasing offset length and decreasing straight length.

**[0061]** The thermal stress was found to be at a minimum when the:

**[0062]** inside diameter of the tubes **308** is approximately 0.9 times the outside diameter;

**[0063]** the length of the tubes **308** is approximately 107 times the outside diameter;

**[0064]** the offset length is approximately 13.3 times the outside diameter;

**[0065]** the length of the straight portions **312***a*, **312***b* is approximately 23.3 times the outside diameter; and

**[0066]** the radius of curvature between the straight portions **312***a*, **312***b* and the curved portion **314** is approximately 13.3 times the outside diameter.

**[0067]** Accordingly, the dimensions of the heat exchanger are preferably as follows:

**[0068]** the diameter of the tubes **308** is approximately 1.0 to 5.0 mm;

**[0069]** the length of the tubes **308** is approximately 100-500 mm;

**[0070]** the length of the curved portion **314** is approximately 30-70% of the total length; and

**[0071]** the offset length is approximately 10-100 mm.

**[0072]** FIG. **12** shows a simulated stress distribution for the heat exchanger **302** under large thermal and pressure loads. As shown, the heat exchanger **302** experiences larger stresses at its centre over the portion **314** as a result of thermal expansion and deformation of the tubes **308**. However, as shown in FIG. **13**, the stress experienced at the centre and at the ends of the heat exchanger **302** is far lower than for the straight tube heat exchanger **2**, and comparable to the U-shaped heat exchanger **102**.

**[0073]** FIG. **14** shows a heat exchanger **402** according to another embodiment of the invention. The heat exchanger **402** comprises an inlet manifold **404** and an outlet manifold **406**. The inlet and outlet manifolds **404**, **406** are fluidically coupled by a plurality of tubes **408** which together form a tube matrix **410**. The tubes **408** of the tube matrix **410** are coupled at one end to the inlet manifold **404** and are coupled at the other end to the outlet manifold **406**.

**[0074]** A plurality of the tubes **408** are aligned in a plane of the longitudinal axes of the inlet and outlet manifolds **404**, **406** to form a row, and several rows are disposed side-by-side to form columns of the tube matrix **410**.

**[0075]** Each tube **408** comprises first and second straight portions **412***a*, **412***b* adjacent the inlet and outlet manifolds **404**, **406** respectively, and a single offset portion **416** disposed between the first and second straight portions **412***a*, **412***b*. The offset portion **414** deviates from a longitudinal axis of the tube **408** between its connection point with the inlet manifold **404** and its connection point with the outlet manifold **406**. As shown in FIG. **14**, the curved portion **414** is offset in a plane of a longitudinal axis of the inlet and outlet manifolds **404**, **406**. The size of the offset from this longitudinal axis is defined as the offset length. The offset portion **416** comprises a third straight portion **418** which is connected to the first and second straight portions **412***a*, **412***b* by first and second angled portions **420***a*, **420***b*. The tubes **408** are curved at the intersections between the first/second straight portions **412***a*, **412***b* and the first/second angled portions **420***a*, **420***b*, and between the first and second angled portions **420***a*, **420***b* and the third straight portion **418**. The third straight portion **418** is arranged such that it is offset from, but parallel with, the first and second straight portions **412***a*, **412***b*. Accordingly, the tube matrix **410** is generally C-shaped.

**[0076]** Again, whilst the gap between adjacent tubes **408** is reduced over the curved intersections of the offset portion **416**, the size of this reduction is minimised. Consequently, the spacing between the tubes **408** at the inlet and outlet manifolds **404**, **406** is not significantly effected.

**[0077]** The offset portion **416** absorbs thermal expansion by elastically deforming. Thus, the offset portion **416** reduces the thermal stress experienced by the heat exchanger **402**.

**[0078]** The first and second straight portions and the offset portion may be integrally formed or may be separate components which are subsequently joined together to form the tube **308**, **408**.

**[0079]** It should be noted that the tubes need not have a circular cross-section and could have any other cross-section, so long as they provide a conduit for the passage of a fluid from the inlet manifold to the outlet manifold.

**1**. A heat exchanger comprising:

an inlet manifold;

an outlet manifold; and

a tube matrix comprising a plurality of tubes, each tube being fixedly connected at one end to the inlet manifold and at the other end to the outlet manifold;

wherein each tube extends generally along a longitudinal axis defined between the connection of the tube with the inlet manifold and the connection of the tube with the outlet manifold, wherein a single portion of each tube is offset to one side of the longitudinal axis; and wherein the tubes are arranged in one or more rows in a plane defined by a longitudinal axis of the inlet and outlet manifolds and a plurality of rows are disposed side-by-side to form columns.

**2**. A heat exchanger matrix as claimed in claim **1**, wherein the tubes are fixedly connected between the inlet manifold and outlet manifold independently from each other.

**3**. A heat exchanger matrix as claimed in claim **1**, wherein the tubes are each separated from an adjacent tube by a substantially similar gap at corresponding portions along the longitudinal axis.

**4**. A heat exchanger as claimed in claim **1**, wherein the tubes are generally C-shaped.

**5**. A heat exchanger as claimed in claim **1**, wherein the offset portion comprises a curved portion which curves away from the longitudinal axis.

**6**. A heat exchanger as claimed in claim **5**, wherein the curved portion has a constant curvature.

**7**. A heat exchanger as claimed in claim **1**, wherein the offset portion comprises a straight portion and pair of angled portions which offset the straight portion from the longitudinal axis.

**8**. A heat exchanger as claimed in claim **1**, wherein the offset portion is offset in a plane defined by a longitudinal axis of the inlet and outlet manifolds.

**9**. A heat exchanger as claimed in claim **1**, wherein a minimum gap between adjacent tubes over the offset portion is greater than ⅔ of the maximum gap between adjacent tubes at the inlet and outlet manifolds.

**10**. A heat exchanger as claimed in claim **1**, wherein the offset portion is 30-70% of the total length of the tube.

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