

Heat Exchanger

The present disclosure relates to a shell and tube type heat exchanger and a method of operating such a heat exchanger. The heat exchanger may have applications in aerospace systems, such as gas turbine engines and hybrid rocket type engines.

Background

Known heat exchangers include shell and tube arrangements which typically comprise a bundle of tubes within a shell. One fluid passes through the bundle of tubes and another fluid passes through the volume of the shell around the bundle of tubes. With the fluids initially at different temperatures, heat transfer between the fluids results. Known arrangements however have limitations in their application due to materials and their associated mass, which can make them unsuitable for applications which call for a light weight and efficient design.

The present disclosure seeks to address and/or at least ameliorate to a certain degree the problems associated with the prior art.

Summary

According to a first aspect of the disclosure, there is provided:

A shell and tube type heat exchanger comprising:

a shell;

a tube arrangement within said shell, said tube arrangement comprising a flow tube, wherein said flow tube furcates at a plurality of nodes along its length; and

a tube matrix fluidly coupled to said flow tube.

Advantageously, with successive furcation or branching of the flow tube, such a tube arrangement can provide for flow tubes with ultimately quite small cross-sections, e.g.. less than 100 μ m diameter, fluidly coupled to a single inlet at one end and fluidly coupled to a tube matrix at the other.

The node points are positions along the length of the flow tube at which the tube furcates or branches.

Optionally, at a respective node or branching point, the flow tube furcates or branches into a plurality of sub-tubes.

The shell may be formed adjacent the tube matrix and the tubes of the matrix may be coupled to the shell with one or more webs or fins. Such an arrangement may advantageously have applications where only one matrix is required such as in low pressure heat exchanger applications. The shell may be formed integrally with the matrix for example, by an additive manufacturing technique. Materials may include metals, for example, 316L stainless steel.

The sub-tubes may be relatively smaller in diameter to the preceding portion of the flow tube such that the diameter of the tubes progressively decrease in size with subsequent furcation. Such an arrangement can provide performance advantages with increasing overall surface area of the increasing number of sub-tubes.

The progressive furcation of the flow tubes into sub-tubes at node points along the length of the flow tube can have a quasi-fractal form. This means that the furcating pattern repeats in an identical or similar manner at each node.

Each respective sub-tube may further furcate or branch at nodes which are aligned, for example in a common flat plane extending generally perpendicular to the extent of the sub-tubes.

Optionally, the respective, corresponding nodes at which furcation or branching occurs in each sub-tube may be offset or may be aligned in a curved plane. Such an arrangement can allow for a more compact branching structure.

The internal cross-sectional area of the flow tube can optionally remain constant or generally constant through or in the region of a furcation or branching node. This means that the total cross-section of the flow tube through the node or branching point remains constant or generally constant as it subdivides. This can avoid pressure concentration in the flow tube at the node points.

The cross-section of the flow tube may be generally circular between the node points. The cross-section of the flow-tube may have a non-circular form, for example a tear-drop shape. The tubes can be configured such that the rounded nose of the tear-drop facing into the flow of the fluid within the volume of the shell. This can reduce pressure drop of the fluid passing through the shell.

The flow tube may be supported by webs which can serve as baffles in the volume of the shell. These can advantageously direct the flow or fluid within the shell and can also avoid stagnant flow regions.

The tube arrangement may have a fluid inlet or outlet for the introduction of a heat transfer medium.

Optionally, the flow tube further comprises a principal furcating node at which the tube inlet furcates into a plurality of sub-tubes.

At each node, the flow-tube may furcate or branch into, for example, two, three or four sub-tubes. At a subsequent node, each of the sub-tubes may each furcate or branch into an equal or different number of further sub-tubes. This furcating or branching pattern may continue to provide an ever-increasing number of sub-tubes.

Optionally, said tube arrangement is formed as a tube module. This can allow for scaling of the heat exchanger. In addition, a modular design allows for modules to be serviced or substituted during service.

The tube module may have a common inlet for all the sub-tubes of the module. The tube module may have a common outlet for all the sub-tubes of the module.

Optionally, the heat exchanger comprises a plurality of tube modules. In this way, the heat exchanger may be sized according to requirements by selecting a number of modules.

Optionally, each of the plurality of tube modules are substantially identical.

Optionally, each of the plurality of tube modules are arranged about a rotational axis of the shell.

Optionally, each of the plurality of tube modules are arranged angularly spaced about the longitudinal axis of the shell.

Optionally, each tube module is connected to a common fluid inlet. The common fluid inlet may be fluidly coupled to a web of tubes which fluidly couple to each module.

Optionally, the plurality of tube modules form a generally ring shaped structure.

Optionally, the ring shaped structure comprises an aperture defined therethrough.

Optionally, the aperture is located on the longitudinal axis of the shell.

Optionally, a plug is provided in said aperture in the ring shaped structure. The plug may have a surface area which is around 10% or less than the overall cross-sectional area of the shell at that point.

Optionally, said tube matrix is provided in said module. Each module may comprise a tube matrix. A tube matrix can provide for a relatively dense arrangement of tubes, for example a spacing less than twice the diameter of a tube within the tube matrix, such as substantially equal to or less than the diameter of a tube within the tube matrix. The flow tubes may progressively furcate into smaller sub-tubes which are in fluid communication with the tube matrix. The section of the module in which the flow tube furcates may provide a manifold for fluid delivery to the matrix. A tube matrix may comprise one hundred, a thousand or more tubes and be sized accordingly to application. The tubes of the matrix may be equally spaced from one another. The tubes of the matrix may be coupled to one another, for example, along their outer edges. The matrix may provide a mass of tubes, which may be arranged in an array. The matrix may be arranged with the tube arrangement within the shell.

The tube matrix may comprise tubes at their minimum diameter in the module. The tube matrix may provide the greatest surface area and hence the majority of heat transfer in the heat exchanger.

The outer profile of the matrix may be shaped dependent on application. For example, the matrix may have an outer profile or perimeter which is in the form of a segment of a ring, a quadrilateral, a circle, or any other shape. This allows the matrix to advantageously fit the profile of the shell or the space or volume in which it is positioned.

The volumetric form of the matrix may be that of a cuboid, a cylinder or any other shape.

Optionally, the tube matrix comprises a plurality of generally parallel tubes. The tubes of the matrix may be arranged spaced from one another, for example in an array. The tubes of the matrix may be arranged in substantially linear rows. The rows may be parallel. The spacing of the tubes of the matrix may be even. The tubes in adjacent rows may be offset from one another and/or aligned in alternate rows.

Optionally, the tube matrix is aligned such that the tubes of the matrix extend axially with respect to the shell.

Optionally, the extent of the tube matrix is positioned generally on a plane perpendicular to the axis of the shell.

Supporting fins or ribs may be provided between adjacent tubes within the matrix. The fins may extend along the full length of a tube in the matrix.

Optionally, discrete supporting fins or ribs may be provided at spaced intervals along the length of the tubes of the matrix between adjacent tubes within the matrix. Such an arrangement of fins or ribs can assist with the accommodation of thermal gradients in the matrix. The spacing of the fins or ribs may be generally equal to the width of the fins or ribs.

The fins may be in the form of substantially planar strips.

Optionally, discrete support fins may be provided at staggered spacing throughout the matrix of tubes. Such an arrangement can reduce mass while still providing benefits in the accommodation of thermal gradients.

Optionally, the tube module may be manufactured using an additive manufacturing process. The matrix may be formed integrally with the furcating and/or consolidating tube sections.

The material of the module may be chosen depending on application. Materials may include stainless steel, such as 316L stainless steel, aluminium and titanium.

Optionally, at the downstream side of the tube matrix each tube consolidates at a plurality of nodes along its length. This successive consolidation of the tubes may be identical or substantially identical in form to the furcation or branching form of the module and those features described in relation to the furcation may be equally applied to the consolidation of the sub-tubes.

Optionally, the tube matrix is located between and fluidly connected to a furcating tube section or manifold and a consolidating tube section or manifold. The furcating tube section and the consolidating tube section may be positioned on opposite sides of the shell with the matrix aligned generally centrally in the shell.

The consolidating tube section or manifold may be coupled to a web of tubes. The web of tubes may couple to each of the tube modules. The web of tubes may have a common fluid inlet/outlet.

Optionally, each tube in the web of tubes may include a section arranged in a spiral, for example a helix. This spiral arrangement of tubes may provide accommodation for thermal expansion or contraction of the tube module or modules within the heat exchanger, but allowing axial movement of the tube.

The spiral may be arranged with its rotational axis aligned with the central longitudinal axis of the heat exchanger shell.

Optionally, the furcation tube section of a module is substantially identical in form to the consolidating section.

Optionally, the shell is rounded.

Optionally, the shell is generally spherical. This allows for a maximum internal volume but with minimum external surface area and thus material. Such a form can also provide a structure which is resistant to internal pressure.

The shell may be formed as a duct, for example, a cylindrical duct. The matrix and flow tube may be provided in said duct. An inlet and outlet to the tube arrangement may extend non-axially to the flow tube, for example, substantially perpendicular. The inlet and outlet may extend through a wall of the shell, for example, the duct, in which the matrix and tube arrangement is provided.

Optionally, the shell comprises a fluid inlet.

Optionally, the inlet of the shell is in fluid communication with the inner volume of the shell via a diffuser. The diffuser may be formed as a flow channel conforming generally to the inner surface of the shell.

Optionally, the shell comprises a thermal liner. Such an arrangement can allow the shell to be maintained at a uniform temperature and thus reduce thermal stresses.

Optionally, the thermal liner substantially conforms to an inner surface of the shell and spaced apart therefrom to form a flow path therebetween. This can allow a small bleed flow of the fluid entering the shell via the inlet.

According to a further aspect of the disclosure, there is provided a method of operating a shell and tube type heat exchanger according to the first aspect and any optional feature thereon, including the steps of:

- supplying a heatant or coolant to the shell to fill said shell;
- supplying a fluid to the tube arrangement in said shell.

The heatant or coolant may be supplied via a diffuser.

A small bleed flow of the heatant or coolant may be supplied to the thermal liner. This can ensure the upstream and downstream sides of the shell are isothermal.

According to a third aspect of the disclosure, there is provided an engine or vehicle comprising a heat exchanger according to first aspect or any optional feature thereof.

Brief Summary of the Drawings

The present disclosure will now be described by way of example with reference to the following drawings, in which:

Figure 1 is a cross sectional view of an example heat exchanger showing a shell and a tube arrangement.

Figure 2 is a partial cutaway perspective view of the heat exchanger of Figure 1 showing a plurality of tube modules.

Figure 3 is a cross-sectional view of the heat exchanger of Figure 1 showing a diffuser.

Figure 4 is a diagram showing progressive layers of a branching manifold.

Figure 5A is a perspective view of a branching manifold.

Figure 5B is a two-dimensional view of a branching manifold.

Figure 6 is a diagram showing an indication of a plurality of flat node planes of a furcating tube arrangement.

Figure 7 is a diagram showing an indication of a plurality of curved node planes of a furcating tube arrangement.

Figure 8 shows a first cross-section view of a node.

Figure 9 shows a series of second cross-section views of a node.

Figure 10A shows a cutaway perspective view of a tube matrix with a continuous fin arrangement.

Figure 10B shows a cutaway perspective view of a tube matrix with a spaced fin arrangement.

Figure 10C shows a cutaway perspective view of a tube matrix with a staggered spaced fin arrangement.

Figure 11A shows a cutaway view of a tube matrix at a constant temperature.

Figure 11B shows a cutaway view of a tube matrix experiencing a thermal gradient.

Figure 12A shows a cross-section view of the heat exchanger highlighting the location of a module mounting.

Figure 12B shows a zoomed-in cross-section view of the heat exchanger showing a module mounting.

Figure 13 shows a perspective view of a branching manifold and a matrix section surrounded by a matrix shell.

Figure 14 is a cross sectional view of an example heat exchanger showing a shell and a tube arrangement.

Figure 15 shows an example of an alternative matrix form.

Figure 16 shows an example of a teardrop tube cross-section.

Figure 17 shows an example of baffle supports present within the shell of the heat exchanger.

Description

Figure 1 shows a heat exchanger generally at 1. The heat exchanger comprises a shell 2, which in the example shown has a generally spherical form. The shell 2 comprises a shell inlet 3. The shell 2 also comprises a shell outlet 4. Both the shell inlet 3 and the shell outlet 4 have a generally circular cross-section. The shell comprises two hemispheres, an inlet hemisphere 27 into which fluid is introduced into the volume of the shell 2 and an outlet hemisphere 28. The shell inlet 3 is located on the surface of the inlet hemisphere 27. The shell outlet 4 is located on the surface of the outlet hemisphere 28. The location of the shell outlet 4 is directly opposite the shell inlet 3.

Situated within the shell 2 is a tube arrangement 5. In the shown example, the tube arrangement 5 extends entirely through the shell 2. The tube arrangement 5 comprises a flow tube 6. The flow tube 6 comprises a flow tube inlet web 29 and a flow tube outlet web 30. The flow tube inlet web 29 is located in the outlet hemisphere 28 of the shell 2, and the flow tube outlet web 30 is located in the inlet hemisphere 28 of the shell 2. The tube arrangement 5 further comprises a tube inlet 7 into which heatant or coolant may be supplied depending upon application. The tube inlet 7 is located in the centre of shell outlet 4 and has a smaller diameter than the shell outlet 4. The tube inlet 7 is also fluidly connected to the flow tube inlet web 29. The flow tube 6 has a tube outlet 8. The tube outlet 8 is located in the centre of shell inlet 3 and has a smaller diameter than the shell inlet 3. The tube outlet 8 is fluidly connected to the flow tube outlet web 30. Both the tube inlet 7 and the tube outlet 8 have a generally circular cross-section.

Referring now to Figures 1 and 2, the section of the flow tube 6 between the flow tube inlet web 29 and the flow tube outlet web 30 comprises a plurality of tube modules 9. In the example, there are eight tube modules 9. The tube modules 9 are substantially identical. The plurality of tube modules 9 are arranged angularly about a longitudinal axis of the shell 2. This angular arrangement of tube modules 9 forms a ring-shaped or generally toroidal structure. When the plurality of tube modules 9 are placed together, they form a generally circular outer profile. The surface of this circular outer profile is generally equidistant at all points from the longitudinal axis of the shell 2. The tube modules 9 are located in a central plane of the shell 2 such that they are spaced substantially equidistant between the shell inlet 3 and the shell outlet 4. The ring-shaped structure of tube modules 9 has an aperture defined therethrough. The aperture

is generally circular in shape and is located on the longitudinal axis of the shell. The aperture is covered or sealed by a centreline plug 16 which blocks the aperture. This prevents the aperture from fluidly connecting the shell inlet 3 and the shell outlet 4. In example, the aperture is around one-ninth the cross-section of the shell 2 equidistant between the shell inlet 3 and the shell outlet 4. Another tube module (not shown) may be used in place of the centreline plug 16.

Each tube module 9 comprises a furcating tube section or manifold 18. Each tube module 9 further comprises a tube matrix 13. Each tube module 9 also comprises a consolidating tube section or manifold 19. The furcating manifold 18 is fluidly connected to the tube matrix 13. The tube matrix 13 is fluidly connected to consolidating manifold 19. Thus, the furcating manifold 18 is fluidly connected to the consolidating manifold 19. The tube arrangement 5 furcates at a plurality of nodes into a plurality of sub-tubes in the furcating manifold 18. The tube arrangement 5 consolidates at a plurality of nodes into a single sub-tube in the consolidating manifold 19. In this way, the surface area of the tube arrangement 5 increases substantially in the furcating manifold 18. The surface area of the tube arrangement 5 is substantially constant in the tube matrix 13. In the consolidating manifold 19, the surface area of the tube arrangement 5 decreases substantially.

The tube module 9 comprises a tube module inlet 10. The tube module inlet 10 is located in the outlet hemisphere 28. Located at the tube module inlet 10 is a node at which the flow tube 6 begins furcating. This node may be known as the principal furcating node. The tube module 9 further comprises a tube module outlet 11. Located at the tube module outlet 11 is a node at which the sub-tubes of the consolidating manifold consolidate to one singular tube. This node may be known as the principal consolidating node. The tube module outlet 11 is located in the inlet hemisphere 27. The tube module inlet 10 and the tube module outlet 11 are fluidly connected to one another. The tube module inlet 10 and tube module outlet 11 are aligned on an axis generally parallel with the longitudinal axis of the shell 2. The tube module inlet 10 is fluidly connected to the furcating manifold 19 and the consolidating manifold 18.

A flow tube inlet web 29 comprises the length of the flow tube 6 from the tube inlet 7 to the tube module inlet 10. The flow tube inlet web 29 is initially a singular tube. The flow tube inlet web 29 then branches into a plurality of module feed tubes at branching point 12.

The flow tube inlet web 29 further comprises an expansion helix 31. The expansion helix 31 allows for axial thermal expansion or contraction of the supported tube modules 9. In other words, the expansion helix 31 allows the heat exchanger to cope with thermal expansion of

tube modules 9 relative to the shell 2. Extreme temperature gradients across the heat exchanger 1 can occur during the start-up of an associated engine, and thus it is important the tube arrangement 5 can accommodate such extreme temperature gradients without undue thermal strain. In the inlet web, each of the module feed tubes is arranged in a helical form. Depending on the number of module feed tubes 6, a double helix, triple helix, may be formed. The expansion helix is located entirely within the outlet hemisphere 28. The expansion helix 31 is also equidistant throughout its length from the longitudinal axis of the shell. After the expansion helix 31, the flow tube inlet web 29 connects to the tube module inlet 10.

Referring to Figure 1, the tube module inlet 10 is fluidly connected to the tube matrix 13. The tube matrices 13 of each tube module 9 are all located in a central plane of the shell 2 such that they are spaced substantially equidistant between the shell inlet 3 and the shell outlet 4. The tube matrix 13 further comprises a tube matrix inlet 14. In this example, the tube matrix inlet 14 is located in the outlet hemisphere 28.

The furcating manifold 18 comprises the length of the tube from the tube module inlet 10 to the tube matrix inlet 14. In the furcating manifold 18, the flow tube of the tube arrangement 5 furcates at a plurality of points along its length into an increasing number of sub-tubes. Each time the tube arrangement 5 splits or branches, the subsequent sub-tubes are each of a smaller diameter than the tube they have split from. In the furcating manifold 18, the angle at which the sub-tubes furcate or branch is substantially regular. The tube arrangement 5 furcates repeatedly from the tube module inlet 10 until it reaches the tube matrix inlet 14. The pattern of furcating sub-tubes substantially repeats itself at decreasing scales of size. The pattern can be considered to be akin to a fractal pattern.

The tube matrix 13 also comprises a tube matrix outlet 15. The tube matrix outlet is located in the inlet hemisphere 27. The tube matrix inlet 14 and the tube matrix outlet 15 are fluidly connected to one another. The tube matrix inlet 14 and tube matrix outlet 15 are aligned on an axis generally parallel with the longitudinal axis of the shell.

The manifold sections 18 and 19 may be formed using an additive manufacturing technique. Materials can be chosen depending on application, such as 316L stainless steel, aluminium and titanium depending on application. This allows for the intricate form of the tube arrangement. The aspect ratio of the tubes, i.e. their internal diameter compared with their external diameter, is limited by the manufacturing tolerances available, in particular the wall thickness.

If additive manufacturing is used, the manifold sections and the tube matrix 13 may be formed as one continuous piece, or produced separately and joined, for example by brazing the manifold sections to the matrix tubes.

The tube matrix 13 comprises a plurality of generally parallel tubes. The tubes of the tube matrix are the smallest-diameter tubes of the tube arrangement 5. The tube matrix 13 is aligned such that its tubes are generally parallel with the longitudinal axis of the shell 2. Between the tube matrix inlet 14 and the tube matrix outlet 15, the tubes of the tube matrix do not furcate nor consolidate. In the example, the matrix of a module comprises over a hundred matrix tubes.

At the tube matrix outlet 15 there are a plurality of sub-tubes. The consolidating manifold 19 comprises the length of tube arrangement 5 between the tube matrix outlet 15 to the tube module outlet 11. The consolidating manifold 19 consolidates the tube arrangement 5 at a plurality of nodes. In this way, the tube arrangement 5 consolidates from a plurality of sub-tubes into a singular tube at each tube module outlet 11. Each time the tube arrangement 5 consolidates, the subsequent sub-tubes are each of a larger diameter than the tubes which consolidated to form them. In the consolidating manifold 19, the angle the sub-tubes consolidate at is substantially regular. The angle the sub-tubes consolidate at is substantially the same angle the sub-tubes furcate at. The tube arrangement 5 consolidates repeatedly from the tube matrix outlet to the tube module outlet 11. The pattern of consolidating sub-tubes substantially repeats itself at increasing scales of size.

The flow tube outlet web 30 comprises the length of the flow tube 6 from the tube module outlet 11 to the tube outlet 8. In the flow tube outlet web 30, the flow tube 6 is initially a plurality of module exit tubes. Each tube module outlet 11 corresponds to one module exit tube. In other words, each module exit tube corresponds to one tube module outlet 11. The flow tube outlet web 30 then joins the plurality of module exit tubes into one single tube at a joining point 17. In the example, this single tube does not branch nor join with any other tube before it reaches the tube outlet 8.

Referring to Figures 1, 2 and 3, the shell 2 further comprises a diffuser 20. The diffuser 20 is located in the inlet hemisphere 27. The diffuser 20 creates a passage between the inner surface of the shell 2 and the diffuser skin 21. This diffuser is for efficiently decelerating the inlet flow with low pressure loss. The diffuser skin 21 substantially follows the curvature of the shell 2. The diffuser skin 21 covers the shell inlet 3. The diffuser passage 79 created between the inner surface of the shell 2 and the diffuser skin 21 is of a generally constant width for the majority of its length. The diffuser passage 79 created between the inner surface of the shell

2 and the diffuser skin 21 is thicker at the shell inlet 3. This is due to the shell 2 at the shell inlet 3 extending out in the longitudinal direction. The diffuser passage 79 between the inner surface of the shell 2 and the diffuser skin 21 is divided by diffuser fins 22. These diffuser fins split the diffuser passage 79 into diverging channels. These diverging channels have a rectangular cross-section. In the example, the inlet-outlet area ratio of the channels is 1:4.

The diffuser 20 further comprises a diffuser outlet 80. The diffuser outlet 80 is located at the end of the diffuser passage 79. The shell 2 further comprises an inlet plenum 23. The diffuser 20 is fluidly connected to the inlet plenum 23 via the diffuser outlet 80. The shell 2 further comprises an outlet plenum 24. The inlet plenum and outlet plenum are fluidly connected. The inlet plenum 23 and outlet plenum 24 are fluidly connected through the spaces between the tubes of the tube matrices 13. The outlet plenum 24 is fluidly connected to the shell outlet 4.

Reference is now made to Figures 1 and 2. The shell 2 further comprises a thermal liner 25. The thermal liner 25 fluidly connects the inlet plenum 23 with the shell outlet 4. The thermal liner 25 maintains the temperature of the outer surface of the shell. The thermal liner 25 ensures the two hemispheres 27 and 28 are reasonably isothermal, by the provision of a small bleed flow of the inlet fluid. This eliminates the high thermal stresses which would result otherwise. The majority of the thermal liner 25 is located in the outlet hemisphere 28 of the shell 2. The thermal liner 25 creates a passage between the inner surface of the shell 2 and the thermal liner skin 26. The thermal liner skin 26 substantially follows the curvature of the shell 2. A first section of the passage extends into the inlet hemisphere 27. A second section of the passage is between the outer surface of the structure of tube modules 9 and the inner surface of the shell 2. The second section of the thermal liner skin 26 is directly adjacent the generally circular outer profile of the tube modules 9. A third section of the thermal liner skin 26 is fluidly connected to the shell outlet 4.

In one typical operation of the heat exchanger 1, the tube arrangement 5 is filled with a heatant fluid. The heatant fluid enters the tube arrangement 5 through the tube inlet 7, and exits the tube arrangement 5 through the tube outlet 8. This heatant fluid can for example be helium. This heatant fluid enters the tube arrangement 5 at around 600K. The shell 2 is filled with a coolant fluid. This coolant fluid enters the shell through the shell inlet, and exits the shell through the shell outlet. The coolant fluid may for example be liquid hydrogen. The coolant fluid enters the shell 2 at a temperature of around 50K and with a flow velocity of around Mach 2 for example. The heatant fluid is at a higher pressure than the coolant fluid. The heatant fluid flows in an opposite direction to the shell fluid providing a counter flow arrangement. This increases the rate of heat exchange compared with if the fluid flows were in the same direction.

Typically, the heatant fluid flows slowest through the tube matrix to increase the amount of heat exchange which can occur.

The furcating and consolidating manifolds 18 and 19 can be considered as forms of branching manifolds. Reference is now made to Figures 4, 5A, and 5B. Figure 4 displays progressive cross-sectional layers of a branching manifold 32, which can be seen in Figures 5A and 5B. In its simplest form, the branching manifold 32 takes the inlet or outlet tube and branches it into four smaller tubes, then each of these branches is divided into four, and so on in progressive layers. The branching is continued until the tube diameter of a tube matrix 44 is reached. Specifically, the first layer 33 of the branching manifold 32 shows a single inlet or outlet tube. The second layer 34 of the branching manifold 32 shows how this single tube, shown by the dotted line, is split into four sub-tubes. These four sub-tubes are of equal diameter. The third layer 35 of the branching manifold 32 divides each of these four sub-tubes into four sub-tubes of their own, generating sixteen sub-tubes in total. These sixteen sub-tubes are of equal diameter. The fourth layer 36 then goes on to divide each of these sixteen sub-tubes into four sub-tubes of their own, generating 64 sub-tubes in total. The fifth layer 37 shows how each of these sixty-four sub-tubes is divided into four, producing two-hundred-and-fifty-six sub-tubes. These two-hundred-and-fifty-six sub-tubes are each of equal diameter. The sixth layer 38 shows how each of these two-hundred-and-fifty-six sub-tubes is further divided into four, producing one-thousand-and-twenty-four sub-tubes. These one-thousand-and-twenty-four sub-tubes are each of equal diameter. In each layer, the sub-tubes are spaced regular distances from one another and form a grid-like pattern. For example, in the first layer 33, the single inlet or outlet tube is drawn as a circle in the centre of a hypothetical square. In the second layer 34, the hypothetical square is split into four sub-squares, and each of the sub-tubes is drawn as a circle in the centre of each sub-square. The branching pattern is repeated for each of the subsequent layers 35-38. This means the diameter of the tubes is constant in each layer. A branching pattern repeated at different scales may be known as a 'fractal'. The tube can be considered as furcating when viewing the layers in sequential order from 33 to 38. Alternatively, the tube can be considered as consolidating when viewing the layers in reverse order, from 38 to 33. The surface area of the tubes increases as tube furcates in sequential order from first layer 33 to sixth layer 38. Alternatively, the surface area of the tube reduces as the tube consolidates in reverse order from sixth layer 38 to first layer 33.

Reference is now made to Figure 6. The branching manifold 32 described above produces sets of 2D (x,y) coordinates for each layer of the branching manifold 32 on which the branching or furcating/consolidating nodes are located. These layers can be assumed to be located on a series of planes, 39-42. The first plane 39 can be considered as corresponding to first layer 33

of Figure 4. The second plane 40 can be considered as corresponding to second layer 34 of Figure 4. The third plane 41 can be considered as corresponding to third layer 35 of Figure 4. The fourth plane 42 can be considered as corresponding to fourth layer 36. The remaining planes 43 can be considered as corresponding to the fifth layer 37 and beyond. The planes 39-43 are flat. At the first plane 39, there is one singular inlet or outlet tube. This tube furcates into a plurality of sub-tubes, two of which can be seen in this two-dimensional cross-section. The branching continues at each plane, until the tube diameter of the tube matrix 44 is reached. As can be seen in Figure 6, the spacing of the nodes between each layer becomes progressively smaller. A divergence angle is the angle at which sub-tubes furcate from a tube. Divergence angle may also be known as turn angle or furcation angle. The branching at each plane occurs at a constant divergence angle.

Reference is now made to Figure 7. It is desirable to seek ways in which the total volume and tube length of the branching manifold 32 is reduced, reducing the total manifold mass. This can be achieved by minimising the distances between the nodes. The branching manifold section of a heat exchanger is typically heavier than the tube matrix with increased surface area it feeds. One way of reducing the distance between the nodes is to manipulate the node coordinates. The lateral distance between the nodes can be reduced with this in mind, which in turn reduces the axial distance of a node for a given divergence angle. This can be achieved by re-shaping the coordinate planes of the nodes into a series of curved surfaces. These curved surfaces may be curved in two or three dimensions. In other words, reducing the distances between each plane of nodes reduces the tube length of the branching manifold 32. Curving the planes of nodes reduces the lateral distance between each plane of nodes. Reducing the tube length between each node by curving the node planes reduces total manifold mass without requiring an increased divergence angle. Not all of the node planes must be curved for the heat exchanger to benefit from their curvature. In the example shown in Figure 7, first plane 35 remains flat. The second plane 46, the third plane 47, a fourth plane 48, and the remaining planes 49 are all curved. The second plane 46 is the most curved, with curvature decreasing in the third plane 47 through to the remaining planes 49. This configuration minimises the divergence angles at each node. This configuration also shortens the early branch stages, which otherwise require the most space to accommodate. This configuration reduces tube length by around one third when compared with a equivalent flat-plane node system with similar divergence angles. The curved-plane technique may be utilised to reduce tube length in both furcating manifolds and consolidating manifolds.

Reference is now made to Figures 8 and 9. A node is a point or location at which a tube subdivides into further sub-tubes. Figure 8 shows a cross-section view of a node 51. Figure 9

shows several cross-sections of the node 51 as one tube splits into several sub-tubes. The nodes must be designed to withstand high internal pressures and to optimise the internal flow conditions which may occur when in use. The ability to manufacture the nodes using an additive manufacturing process is also important. Pressure drop throughout a tube arrangement is increased if its cross-sectional area is increased at nodes compared with a gradual increase in cross-sectional area between the nodes.

The node can be considered as being split into two phases, phase one and phase two. Phase one is a single straight pressure vessel before the branches split. Phase two is a number of pressure vessels that diverge from the original centreline of the node 51. These two phases ensure stress concentrations in the node's walls are limited. In phase 1, a set of fins gradually extend from the internal walls of the node 51 to meet in the centre. This splits the flow into a plurality of sectors. In this example, there are four sectors. During this phase, the overall diameter of the tube must increase to account for the cross-sectional area taken up by the fins. The section remains circular because all of the pressure loads are taken by the walls of the node 51. In phase 2, which occurs once the fins are merged at the centre, the now separates flow sectors now diverge. In geometric terms, the centroid of each channel follows a circular path away from the node's original centreline. This causes the cross-section to adopt a lobed shape as the outer radius shrinks. During this phase, pressure loads are transferred to the fins. This allows the node wall thickness to decrease. The node thus allows a transition from a single circular section tube to multiple circular section tubes.

The node cross-sections depicted in Figures 8 and 9 are scaled such that the flow area remains constant through the node. If the cross-section of a manifold increases from its inlet to its matrix section, this means that the total cross sectional increase between an inlet and a beginning of a matrix of a heat exchanger is accommodated in the straight tube sections between the nodes. Alternatively, the cross sectional area of the whole manifold can be scaled linearly from its inlet to the beginning of the matrix.

Sections 52-57 correspond to phase 1 of the node 51. The cross-section of section 52 is circular with a relatively thin node wall 64 around the perimeter of the section. The cross-section of section 53 has four fins 65 beginning to protrude from four corners of the node wall 64. The nodes continue to grow from section 54 through section 55 and section 66, until they join in the middle of the node at section 57. The joined fins 65 form an 'x' shape in the centre of the node 51, with four empty sections closed off from one another between the joined fins 65 and the node walls 64. At 57, the joined fins 65 are of greater thickness than the node wall 64. Sections 58-63 correspond to phase 2 of the node 51. The cross-section of 58 of the node

51 features a thinner node wall 64 than previous cross-sections. The node wall 64 reduces through cross-sections 59 and 60, before a central, circular cavity is formed in the middle of the "x" of joined fins 65 enclosing four cavities in cross-section 61. In cross-section 62 the four cavities are separated, forming four separate circular tubes. The node walls of each of these four circular tubes are thinner than the node wall 64 of initial section 52. These four circular tubes are located further away from each other in cross-section 63. Each of the cross-sections 52-63 are symmetrical in two perpendicular axes.

Reference is now made to Figures 10A, 10B, and 10C. To facilitate manufacturing and to assist with regular tube spacing, a plurality of matrix tubes 68 are supported along their length. In the most basic implementation, this can be achieved by continuous fins 65 in all regular grid directions, shown in Figure 10A. With continuous fins, assuming a similar fin thickness to the tube wall thickness, there can be an increase in the overall matrix mass. The pressure drop of a fluid within the shell passing through the tube matrix from an inlet hemisphere to an outlet hemisphere can also increase due to the reduction in flow area.

The mass of the fins can be further reduced by replacing the continuous support fins 65 with discrete support fins spaced at regular intervals, known as spaced fins 65 seen in Figure 10B. This reduces the volume and mass of material needed to be used for the construction of the support fins. In the example shown in Figure 10B, the spaced fins are of a broadly rectangular shape. Around 50% of each tube's length is used by the spaced fins.

This principle of weight reduction can be implemented further by staggering the support fins to support along a single grid direction at each point along each tube's length. The staggered support fins 67, shown in Figure 10C, cycle through the grid-directions sequentially along each tube's length. In the example shown, only one spaced fin is required when staggered where six were previously. The staggered support fins have the potential to reduce the volume and mass of the matrix section supports by five-sixths, or 83%, compared with spaced fins 65.

The use of spaced fins 66 also allows for the easier accommodation of thermal gradients. This is particularly valuable with respect to non-linear starting transients. Being able to accommodate thermal expansion is of high importance with respect to a tube matrix section to prevent features from breaking up. Figure 11A shows a two-dimensional cross-section of a matrix section, with the plurality of matrix tubes 68 running substantially parallel with one another, connected by spaced fins 66. Figure 11B shows a two-dimensional cross-section of the same matrix section, but with a non-linear thermal gradient 69. The non-linear thermal gradient 69 shows an increase in temperature in the indicated direction. As the temperature

increases, the spaced fins 66 between the matrix tubes 68 grow in size. The spaced fins 66 being allowed to expand in this way results in lower thermal stresses compared with a continuous fin arrangement 65. This causes the spacing between the tubes 68 to be increased by the support fins 66 of higher temperature.

The fins can be formed integrally with the matrix tubes 68 using an additive manufacturing technique.

Reference is now made to Figures 12A and 12B. The heat exchanger 1 is of the same structure as shown in Figure 1. Figure 12A shows a cross-section of the heat exchanger 1. Figure 12B shows an enlarged view of the section encircled at 78 in Figure 12A. At a corner of a tube matrix 13 of one of the plurality of tube modules 9, the tube module 9 is mounted on the inside surface of the shell 2. Figure 12B shows the tubes 70 of the furcating manifold 18. These furcating manifold tubes 70 then enter the tube matrix 13. The furcating manifold tubes 70 continue in the tube matrix 13 as a plurality of tube matrix tubes 71. The tube matrix 13 features a spaced fin configuration 72. The spaced fins 72 support the tube matrix tubes 71. At the outside edge of the tube module 9, the spaced fins join a module jacket 76. This module jacket allows the tube module 9 to be mounted to the shell 79 of the heat exchanger 1. The tube module 9 is surrounded by the module jacket 76 for the full length of the tube matrix 13. This ensures the flow through the shell 2 is constrained to being through the tube matrix 13. The module jacket 76 features a module jacket flange 73. The module jacket flange 73 extends perpendicularly from the tube matrix 13. The module jacket flange 73 has a thicker wall than the section of the module jacket 76 running the full length of the tube matrix 13. The angle between the module jacket flange 73 and the module jacket 76 is ninety degrees. A module mount frame 75 extends from the inside surface of the shell 79. The module jacket flange 73 is adjacent the module mount frame 75. There is a gap between the module jacket flange 73 and the module mount frame 75. This gap is filled by a gasket 74 or a similar seal. This seal is gas-tight.

Reference is now made to Figure 13, which shows an alternative branching manifold 132 having a similar branching structure to the furcating manifold 18 and consolidating manifold 19 of the example shown in Figure 1 and in more detail in Figure 5A. In contrast though, the arrangement shown in Figure 13 is a heat exchanger 100 with a single module and may have low pressure applications.

A tube matrix 113 comprises a plurality of matrix tubes, which in the example are generally parallel arranged tubes. The matrix tubes located around the outer edge, or periphery, of the

tube matrix 113, are considered outer matrix tubes. The tube matrix 113 is surrounded by a matrix shell 181. The matrix shell 181 substantially conforms to the outer edge or profile of the tube matrix 113. This ensures a coolant fluid entering a first side of the matrix shell 181 and exiting a second side of the matrix shell 181 remains substantially within the outer limits of the tube matrix 113 when flowing from the first side to the second side of the matrix shell 181, between the tubes of the tube matrix 113. The matrix shell 181 is a relatively thin layer of material, and has a corrugated outer surface 182 with a plurality of substantially parallel ridges 183 and grooves 184 running parallel to the tube matrix 113. The corrugated outer surface 182 gives the matrix shell 181 added rigidity and strength over a matrix shell example having a smooth outer surface.

The matrix shell 181 is connected to the tube matrix 113 via a plurality of webs or fins. The matrix shell 181 may be connected to the outer matrix tubes via the plurality of webs or fins. The webs or fins may be in continuous, spaced, and/or staggered configurations. The matrix shell 181 may also be used in shell and tube heat exchanger configurations limited to one tube matrix. As with the matrix of Figure 1, the tube matrix 113 can be manufactured using an additive manufacturing technique. In addition, the shell 181 can be integrally formed using the additive manufacturing technique with the tube matrix 113.

Figure 14 shows a further heat exchanger arrangement generally at 201 comprising a single matrix heat exchanger module with a generally cylindrical tube matrix 213. The heat exchanger comprises a shell, 202, which in the example shown has a generally cylindrical form. The shell 202 comprises a shell inlet 203 into the volume of the shell 202, and a shell outlet 204, located at opposite ends of the shell 202. The shell inlet 203 and the shell outlet 204 are aligned substantially axially at the opposite ends of the shell 202.

The arrangement of Figure 14 has a similar branching configuration as the arrangement of Figure 1. The tube arrangement 205 comprises a tube inlet 207, a tube module inlet 210, a furcating manifold 218, a tube matrix 213, a consolidating manifold 219, a tube module outlet 211, and a tube outlet 208. The furcating manifold 218, the tube matrix 213, and the consolidating manifold 219 are similar in form to the furcating manifold 18, the tube matrix 13, and the consolidating manifold 19 of the example of Figure 1. The tube inlet 207 is fluidly connected to the tube outlet 208. This example comprises only one tube matrix, and therefore there is no joining point or branching point as seen in the first example. As such, the tube inlet 207 is directly connected to the tube module inlet 210, and the tube outlet 208 is directly connected to the tube module outlet 211. The tube inlet 207 and tube outlet 208 are axially aligned with respect to the tube matrix 213. The tube inlet 207 enters the shell 202 through a

side wall of said shell 202 which is a cylindrical with semi-elliptical ends. The tube outlet 208 also exits the shell 202 through a side wall of said shell. The tube inlet 207 and tube outlet 208 may enter and exit respectively the shell 202 through the same side wall of said shell. The tube matrix 213 is mounted to the shell 202. This mounting may be in a similar manner to that discussed in relation to the example of Figures 12A and 12B, and ensures the flow through the shell 202 is constrained to being through the tube matrix 213. Although not shown, the heat exchanger 201 may have all of the optional features discussed in this application, for example the expansion helix, node structure, and matrix support fins.

Reference is now made to Figure 15 which shows an example tube matrix of cylindrical form. This example shows a tube arrangement comprising three sections: a furcating manifold 318, a tube matrix 313, and a consolidating manifold 319. For clarity, the parts are showed in exploded form although it should be understood that the parts would be adjoining to provide a fluid coupling between the parts. The furcating manifold 318, tube matrix 313, and consolidating manifold 319 are similar in structure to the furcating manifold 18, tube matrix 13 and consolidating manifold 19 of the example of Figure 1. The tube matrix 313 further comprises a tube matrix inlet 314 and tube matrix outlet 315. The tube matrix 313 may be shaped such that it can conform to any defined space, as required, allowing it to effectively fill it. For example, the tube matrix 313 may be shaped to conform to a duct, filling the duct profile. The tube matrix 313, when viewed axially, may have a profile with curved sides, a straight-sided profile, or a profile which is a combination of straight and curved. In this example, the tube matrix 313 has a substantially cylindrical form. The furcating manifold 318 is in fluid communication with the tube matrix 313. The consolidating manifold 319 is in fluid communication with the tube matrix 313. Thus, the furcating manifold 318 is in fluid communication with the consolidating manifold 319 via the matrix 313. The furcating manifold 318 and consolidating manifold 319 are located on opposite sides of the tube matrix 313. The furcating manifold 318 comprises a plurality of sub-tubes. The furcating manifold sub-tubes at a minimum diameter are adjacent to and in fluid communication with the tube matrix 313, and form a matrix inlet face 385. The consolidating manifold 319 comprises a plurality of sub-tubes. The consolidating manifold sub-tubes at a minimum diameter are adjacent to and in fluid communication with the tube matrix 313, and form a matrix outlet face 386.

Reference is now made to Figure 16 which shows a tube cross-section with a teardrop-shaped perimeter. The teardrop shape has a first portion which is generally semi-circular in form and adjoins second portion which converges at a point. A teardrop shape typically has one line of symmetry upon which the point of the second portion lies.

It is desirable to seek ways in which the pressure drop of a shell fluid through a shell is reduced. The branching manifolds of previous examples discussed, e.g. the furcating manifolds 18 and 318 and the consolidating manifolds 19 and 319, comprise a plurality of tubes and are typically situated within a shell through which a shell fluid flows when the associated heat exchanger is in operation. The branching manifolds can generate drag which contributes to pressure drop of the shell fluid.

The tubes of the branching manifolds may have teardrop (or aerofoil) shaped cross-sectional perimeters. These tubes may be oriented with respect to the direction of the shell fluid flow within the volume of the shell such that drag is reduced, thereby reducing pressure drop of the shell fluid.

The concept of branching manifolds with teardrop-shaped tubes is not limited to any shape of shell.

Reference is now made to Figure 17, which shows the heat exchanger of Figure 1, but with a plurality of baffle supports 88.

The plurality of baffle supports 88 extend into the volume of the shell and may be attached to the inner surface of the shell. The plurality of baffle supports 88 may be located between or attached to the branching manifolds (furcating manifold 18 and consolidating manifold 19) of each tube module 9. Although in the example, the baffle supports 88 are generally linear strips, the baffle supports 88 may have alternative shapes and forms to direct the flow of the fluid within the shell. Preferably, the plurality of baffle supports is shaped to provide minimal resistance to, and thus pressure drop of, the shell fluid flow. In this example, each baffle support 88 is substantially planar, and extends through the volume of the shell until the central aperture. The plurality of baffle supports 88 act as turning vanes for the shell fluid.

Applications of the heat exchanger can include such as gas turbine engines and hybrid rocket type engines for example for aerospace uses.