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DRAWINGS ATTACHED



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(54) HEAT TRANSFER STRUCTURE

(71)¹ We, RAYTHEON COMPANY, a corporation organized under the laws of the State of Delaware, United States of America, of Lexington, County of Middlesex, Commonwealth of Massachusetts, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The efficient transfer of heat as well as the efficient and economical conversion of thermal energy between flowing fluids and media to be heated or cooled is highly desirable in the present day art. The areas of interest reside in the home, for example, in cooking and heating, and in industry in numerous industrial processes such as condensation, distillation and heating. In the heat transfer art the completeness of extraction of thermal energy between a heated flowing fluid and another medium is the parameter of primary concern. In normal fuel burners, for example, with limited heat transfer area are exhaust temperatures which may be a few hundred degrees indicate that a considerable amount of available heat in the fuel is not utilized and is lost through the flue. Efficiencies of between 50 and 60 percent are, therefore, quite usual in present day thermal energy conversion devices.

Increasing the transfer area between the flowing fluid and the medium to be heated through baffles, plates, or other obstructions has not met with marked success in improvement of heat transfer efficiencies. An expression often utilized in the art to described the heat transfer characteristics is "power density" which denotes the thermal energy per unit of time flowing through a unit of area of a body to be heated. Prior art devices have normally observed power densities of less than 100 watts per square inch of transfer area. This indicates that with the numerous high thermal energy sources available such as, for

example, a direct flame having a 7 kilowatt output capability higher efficiencies will be realized if the power density characteristic of the transfer structure can be suitably enhanced. The object of this invention is to provide improved structure to achieve much higher efficiencies with power densities 10 to 100 times those normally achieved in the transfer of thermal energy.

In accordance with the present invention, there is provided a heat exchange structure for transferring heat between first and second fluid media through a thermally conductive solid structure which incorporates a passageway for the first medium and a plurality of flow paths for the second medium, which paths are defined between a plurality of layers of bodies forming a matrix and whose surfaces, which form the elemental surface areas of the flow paths, and predominantly convexly curved in all directions, wherein the average length of the flow paths is not greater than 15 times the average radius of curvature of the said elemental surface areas.

The interstices between the bodies in the matrix define tortuous flow paths for a fluid heating or cooling medium. The said passageway provides for the passage of another medium at a lower or higher temperature than the heating or cooling medium within the flow paths of the matrix. The matrix may be provided by joining together thermally conductive bodies through conventional brazing, sintering or soldering techniques by coating the individual bodies with suitable materials having characteristics for such metallurgical processes.

Another term used in explaining and defining the present invention is "characteristic dimension". This term means the average distance between opposed boundaries of the said passageway between which the matrix lies. In a circular configuration with an internally contained matrix, the characteristic dimension will be the diameter of the con-

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duit containing the matrix. In the flat or planar configuration having spaced parallel thermally conductive walls with the barrier matrix structure disposed therebetween the term denotes the distance between the parallel walls. In configuration providing spaced sections of the said passageway embedded in an external barrier matrix the term means the average distance between adjacent sections.

Various embodiments of the present invention will be described including fluid passages embedded within an optically dense barrier matrix. Such a structure will provide an efficient domestic hot water source and may be advantageously disposed at any desired utilization point. Another embodiment of the invention incorporates the disposition of thermal conductive bodies within as well as surrounding a conduit to accommodate heat power densities as high as 10,000 watts per square inch for applications such as, for example, boilers for furnaces. The high efficiencies realised with the disclosed embodiments will result in substantial reductions in space and cost of heat transfer modules.

The invention will now be described in more detail, by way of example, with reference to the accompanying drawings in which:

Fig. 1 is a vertical cross-sectional view of an illustrative embodiment of the invention for heating of a circulating liquid by an external matrix structure;

Fig. 2 is an enlarged fragmentary view of a portion of the external matrix included within the line 2-2 in Fig. 1;

Fig. 3 is a sectional view taken along the line 3-3 in Fig. 1 viewed in the direction of the arrows;

Fig. 4 is a diagrammatic representation of the principal optimum parameters of the illustrative embodiment;

Fig. 5 is a diagrammatic representation of a flat heat transfer unit;

Fig. 6 is another diagrammatic representation of an embedded external barrier matrix structure;

Fig. 7 is a schematic representation of a complete system utilizing the heat transfer unit illustrated in Figs. 1 to 3;

Fig. 8 is a vertical sectional view of an alternative embodiment of the present invention;

Fig. 9 is a horizontal sectional view taken along the line 9-9 in Fig. 8;

Fig. 10 is a vertical sectional view of another embodiment of the invention designed to provide high power density operation;

Fig. 11 is a vertical sectional view along the line 11-11 in Fig. 10;

and Fig. 12 is a fragmentary partially sectioned view illustrative of an alternative embodiment of the invention.

In the drawings, Figs. 1, 2, and 3 illustrate a preferred embodiment of the invention.

Before proceeding to the detailed description, however, it will be of assistance to refer to Figs. 4, 5 and 6 and a description of the important conceptual aspects of the invention.

A heat transfer arrangement which provides for a high thermal transfer rate utilizing a structure to provide optimum power density along a heat flow path is illustrated in Fig. 4. Thermally conductive bodies are metallurgically bonded along contiguous surfaces to define an optically dense barrier matrix 11 along a fluid flow path. The interstices between the bodies define a plurality of tortuous fluid flow paths. Spherical bodies, such as shot or ball bearings, have been shown although similar results are attainable with other similarly arranged bodies, the configuration and dimensions of which meet the critical parameters required by the invention. Suitable thermally conductive materials include copper, brass, stainless steel carbon steel, aluminium, as well as any of the synthetic plastics materials embedded with metallic particles. Ferrous or copper bodies may be coated with a copper-silver eutectic solder and the overall matrix structure may be conglomerated by any of the well known processes including brazing, sintering or welding. A dip brazing technique is required for aluminium conductive members.

Achievement of the maximum average size for the body members to secure an optically dense matrix in the shortest distance possible along the direction of fluid flow is one of the design criteria to be followed in the practice of the invention. A fluid flowing along a path indicated by arrow 13 will encounter the optically dense structure which is joined to a surface of a conducting wall 12, on the other side of which another fluid flows. Through the provision of a number of bodies 10 arranged to provide tortuous flow paths in the optically dense barrier matrix the total overall efficiency of the heat transfer device is enhanced. The path of the thermal energy flow from the flowing fluid through the matrix 11 adjacent the wall 12 is indicated by the arrow 14, to result in transfer to the medium contacting the opposing surface 15 of the wall.

Another criterion which can be considered in the provision of an efficient heat transfer structure in the shortest distance possible along the heat flow path concerns the number of bonded joints or junctions in any direction from the point of thermal contact along a heat path to the nearest adjacent conducting interface with the passageway. Referring to Fig. 5, a matrix structure 16 is shown disposed between spaced interface walls 17 and 18 on the outside of which the other fluid flows. The fluid flow path for the heating or cooling fluid is indicated by the arrow 19. It has been discovered that optimum results will be obtained with an optically dense arrangement when the average number of contiguous

bonded joints is from the point adjacent interface

Another critical characteristics designated by between the p 18. To achieve with an optically heat path to t a flowing fluid be depicted arrows 20 and the heat path fluid at any nearest point then may be s teristic dimens average size approximately dimension of stantially lar above one-ha sion, would sufficiently of fact, such a efficient in the the other extr ductive bodie one-sixth of violate on o number calle requirement conductivity device.

Fig. 6 illustrates the flow of barrier matrix directed in t as indicated is referred to the design c

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bonded joints in a desired heat path direction from the point of contact to the nearest adjacent interface surface is about two.

- Another criterion of interest concerns the characteristics dimension shown in Fig. 5 and designated by the arrow C.D. as the distance between the parallel boundary walls 17 and 18. To achieve the highest heat transfer rates with an optically dense barrier structure the heat path to the nearest boundary surface for a flowing fluid directed along path 19 may be depicted by perpendicularly directed arrows 20 and 21. The maximum length of the heat path through the matrix from the fluid at any point in the matrix to the nearest point in the nearest boundary surface then may be seen to be one-half of the characteristic dimension of the device. Preferably the average size of each of the bodies shall be approximately one-third of the characteristic dimension of the device. Bodies of substantially larger dimensions, for example, above one-half of the characteristic dimension, would not collectively define a sufficiently optically dense arrangement. In fact, such a device would be highly inefficient in the transfer of thermal energy. At the other extreme of the range, thermally conductive bodies of smaller diameters below one-sixth of the characteristic dimension violate an optimum designed characteristic number called the number of brazed joints requirement and thereby lower the thermal conductivity efficiency of the heat transfer device.

Fig. 6 illustrates an embodiment of the invention wherein spaced conduits for directing the flow of a fluid are embedded in the barrier matrix and a second flowing fluid is directed in the region between the conduits as indicated by arrow 22. This configuration is referred to as the external type and again the design criteria of the number of bonded

joints as well as optical density of the matrix are applicable. A circular conduit 23 which may comprise a linear array of parallel members or a helical coil is embedded in the barrier matrix 24 of thermally conductive bodies. The characteristic dimension of this configuration is calculated between the conduit wall surfaces and is derived by averaging the maximum and minimum dimensions A and B of the spacing between the conduits. Thermal energy directed along path 22 will traverse heat paths indicated by arrows 25 and 26 to the adjacent conduit walls. Again, as in the example shown in Fig. 5, the maximum length of the heat path from any point in the matrix is desirably one-half the characteristic dimension or average distance $(A+B)/2$ between the spaced conduit walls. The average number of brazed joints is about two from point of impact of the second fluid and the average size of the bodies will be between one-half to one-sixth of the characteristic dimension for the requisite density.

The high heat transfer rate or increased power density achieved by the invention is believed to be attributable to the large number of surfaces provided by the conductive area of each of the matrix body members, turbulent flow and the very short heat transfer path to the boundary surface. Relatively high power densities are attainable in embodiments of the invention to be hereinafter described and may be as high as 1,000 watts per square inch of the area of the conduit forming the passageway for the first fluid. Compared with embodiments of conventional prior art structures capable of handling power densities of less than 100 watts per square inch it is apparent that a substantial improvement has resulted. A useful empirical equation in the determination of the design criteria incorporating the teachings of the invention is as follows:

$$(1) \text{ Heat path length } (L) = \frac{(\text{temp. drop}) \cdot (\text{conductivity or material})}{\text{heat flux}}$$

- Using self consistent units, the length L is given in terms of the unit of length used in the conductivity and heat flux. The term "heat flux" refers to input thermal energy and may be expressed in terms of British thermal units per hour per square feet of wall area of the interface boundary through which the heat is transferred. Thermal conductivity of the material is a constant value and is readily determined from tables for that purpose. This term indicates the quantity of heat that will flow across a unit area of the body heated if the temperature gradient is unity. As stated previously the heat path length represents one-half of the charac-

teristic dimension. The matrix body member dimensions can then be readily computed from this value of characteristic dimension. The application of this equation will be demonstrated hereinafter in relation to one of the described embodiments.

In Figs. 1, 2 and 3 a highly efficient and practical embodiment of the present invention is illustrated and will now be described. A helical conduit 30 forming a passageway for a first fluid is embedded in and surrounded by an external sintered barrier matrix 31. The matrix 31 is composed of discrete thermally conductive bodies small enough to provide for the optical density and the second

fluid passes through the flow paths through the matrix. The thermal conductivity, pressure drop limits and power density will determine the pitch, diameter and overall length of the conduit to arrive at the maximum allowable heat path and this in turn will determine the characteristic dimensions. The matrix design criteria are then determined from the characteristic dimension value.

It will be seen from Fig. 1 that the length of the gas flow paths through the matrix is that provided by 6 to 7 layers of balls, that is to say this length is less than 15 times the average radius of curvature of the surfaces defining the flow paths, the average radius of curvature being synonymous with the radius of the balls in an embodiment using equal sized balls as illustrated. It can also be seen from inspection of the drawings that the other embodiments described below have even shorter flow path lengths in terms of the said average radius of curvature.

An inlet 32 and outlet 33 are, respectively, connected to a water source and the point to which the hot water is to be supplied. The embedding of the conduit in the barrier matrix can be achieved by positioning the helical conduit 30 within a cylindrical space defined by two concentrically disposed tubular jig members of a material which will not bond to the body members whose dimensions are related to the characteristic dimension value. The jig members have different diameters and the circular space between these members may be filled with the individual body members. Shaking and vibrating of the over-all assembly will provide for the desired array of the bodies around each of the conduit turns. The entire assembly is then metallurgically treated at the requisite temperature and the jig members may be separated. The combined external barrier matrix structure and conduit is then assembled in the embodiment and a central combustion chamber 38 is defined by the heat transfer matrix.

Typically, a barrier plate member 34 may be provided with a plurality of passageways 35 for the admission of an air-gas mixture under pressure from a source coupled to conduit 36 and fitting 37 into the combustion chamber 38. Angularly and laterally disposed within the burner plate member 34 is an ignition means 40 of any well known construction such as a spark plug to provide the necessary ignition of the gaseous fuel mixture. An outer wall 41 surrounds the heat transfer structure and a flue 42 for the passage of the exhaust gases extends to a conventional flue (not shown). A top plate 43 is suitably secured to the heat transfer structure and conduit such as by nuts and bolts 44, part of which bolts may also be embedded in the matrix.

In an exemplary working embodiment a

heat transfer unit as described in Figs. 1 to 3 having dimensions of about five inches in diameter and about five inches in length was utilized to provide a continuous hot water flow of approximately three gallons per minute. The burner driving the heat transfer unit and all the electrical controls including a thermostat, air filter and safety regulating devices were incorporated into a structure having a height of about six inches, a width of about twelve inches and an overall length of about eighteen inches. Such a heat transfer module can replace conventional present day hot water heaters of the storage tank variety having diameters of approximately two feet and heights of approximately six feet. The new improved structure can be very conveniently mounted adjacent to the final utilization point. In view of the exceedingly low cost many such devices can also be incorporated with resultant savings in cost of piping and plumbing necessary with present day centralized domestic hot water heating systems.

Referring now to Fig. 7, the embodiment of the invention shown in Figs. 1-3 together with the appurtenant structure, is collectively referred to as a heat transfer module designated by the numeral 50. An air blower 51 is coupled through the fitting 37 to feed the air and gas mixture into the combustion chamber 38, being arranged to provide an energy transfer rate of more than 100 watts per square inch at the surface of the conduit 30. A gas from source 53 which may be any commercially available natural or tank type, is fed through a solenoid control valve 54 and regulator 55 to the inlet 52 in blower 51. Any small size blower of the inexpensive variety should suffice for most applications. The vent 42 extending laterally from the heat transfer module 50 will provide for the egress of the combustion gases to a convenient flue. Due to the efficiency of the heat transfer and the fact that the exhaust temperature is exceedingly low a small vent opening in a wall may be used similar to the type employed in home clothes dryers. No natural draught type chimney is required, which also results in savings in construction costs. The water supply is indicated by numeral 56 and the heated water is fed through line 57 to the outlet tap 58 for instant usage. A temperature and pressure relief valve 59 may be disposed in line 57. It is thus noted that large storage tanks or bodies utilized in present day hot water generation sources are completely eliminated. A compact and unique source is thus disclosed which may be readily installed directly in the area where the use is intended, for example, the bathroom or kitchen.

Associated wiring for the control of the blower as well as the thermostat and ignition controls together with the main solenoid valve

for the gas described, available at such means.

In Figs. 5 conduits 6 matrix 62 bodies as An upper inlet pipe means 65 member 6 structure 6 which are conduits 15 with a collar member is disposed structure 20 and adjacent communicates collar member ends of fluid outlet 25 collar member further has gas-air mixture conduit 74 bustible furnished the upper.

Figs. 10 embodiment 10 tions. In 35 78 are dis outer components 79 pipe 81 medium a the egress or heated at the medium gas flame of this col

The char twice the thermally between one therefore optimum one-sixth is preferred

In Fig. 100 illustrated plurality matrix 91 vide the bodies su

for the gas source have not been specifically described, since they are readily commercially available and normal techniques incorporating such means will be followed.

- 5 In Figs. 8 and 9 a linear array of fluid conduits 61 is embedded within a barrier matrix 62 composed of thermally conductive bodies as have hereinbefore been described. An upper plate member 63 supports a fluid inlet pipe 64 and is secured by fastening means 65 to screws 66 embedded in a collar member 67. The optically dense matrix structure 62 surrounds the linear conduits 61 which are embedded therein, the ends of these conduits and the inlet 64 all communicating with a channel 68 in the inner side of the collar member 67. A similar end arrangement is disposed at the opposite end of the matrix structure including a lower plate member 71 and adjacent collar member 70 and communicates with an inner channel 68a in collar member 70 with which the adjacent ends of conduits 61 also communicates. A fluid outlet pipe 72 is supported by the lower collar member 70. The plate member 71 further has a plurality of passages 73 for a gas-air mixture fed into the device through conduit 74. The ignition means for the combustible fuel within the chamber 75 is furnished by a spark plug 76 supported by the upper plate member 63.

- 5 Figs. 10 and 11 are directed to an embodiment for very high power density applications. In such embodiments conduits 77 and 78 are disposed about a common axis. The outer conduit 77 is closed by conductive plates 79 and 80 at opposing ends. An inlet pipe 81 provides for the ingress of a fluid medium and an outlet pipe 82 provides for the egress of the medium in the vapourised or heated state. The inner conduit 78 is open at the ends for the flow of a heated fluid medium such as the gases from an oxygen-gas flame directed along the inner passage 83 of this conduit, with the direction of flow be-

ing indicated by the arrow 84. An optically dense barrier matrix structure 85 comprises a plurality of thermally conductive spherical members joined together to define the flow paths for the heated fluid. The barrier structure 85 occupies a major portion of the cross-sectional area of the conduit 78 and the characteristic dimension of this member will be the inner diameter of the circular conduit as designated by the arrow 86 and symbol C.D.

A similar barrier matrix 87 occupies the cross-sectional area of the outer conduit 77. With the internal barrier matrix structure 85 occupying only a portion of the overall length of the passage 83 for concentration of the heated medium, the heat transfer area between the medium in the respective conduits will occur substantially in the region indicated by the bracket 88. This configuration then provides for higher density applications.

An example of the application of the previously enumerated equation (1) in the transfer of heat from an intense heat source may be noted in the higher power density embodiment of Figs. 10 and 11. Utilizing a direct flame source in the passage 83, we assume that a power density of 1000 watts per square inch of flame area is obtained, i.e. 0.5×10^6 BTU/sq.ft./hour, and yet silver brazed copper members may be employed. Additionally, it is assumed that a desired temperature rise of the heated medium of 1000 degrees Fahrenheit is specified. Copper has a thermal conductivity value of about 200 BTU/hour/ft. 2 /°F. In the final structure we assume that a lower conductivity will be realized due to the brazed joints and optical density of the thermal paths. A conductivity factor of 50 per cent, i.e. a conductivity of 100 BTU/hour/ft. 2 /°F, then will provide a reliable design factor. Utilizing the other known values the heat path (L) is calculated as follows:

$$L = \frac{100 \times 100}{0.5 \times 10^6} = 2 \times 10^{-2} \text{ feet} = \text{approximately } 1/4 \text{ inch}$$

The characteristic dimension will then be twice the heat path value or 1/2 inch. A thermally conductive body average size of between one-quarter and one-twelfth of an inch therefore is indicated for the required optimum optical density. A one-third value or one-sixth of an inch for thermal body size is preferred in most applications.

- 100 In Fig. 12 another embodiment is illustrated. A helical conduit having a plurality of turns 90 is embedded within a matrix 91 of the external type. If we provide the proper design criteria for the matrix bodies surrounding the conduit the interior

passages thereof may be filled with other conductive members which need not meet these same critical requirements. Hence, in applications where steam is generated and in condensation devices particles such as mesh, wires, shavings, cuttings and the like can be employed, as indicated collectively by numeral 92. Such a configuration for the obstructions within the conduit will provide for even wider application of the invention in industry.

The advantages of compactness and efficiency of the disclosed thermal transfer device in the provision of vastly improved power densities through the optically dense matrix

structure will now be apparent to those skilled in the art from this description. The design criteria of the number of bonded joints along the heat path and the average size of the thermally conductive bodies in relation to the characteristic dimension to provide the desired optical density have been carefully enumerated. The foregoing discussion and exemplary application of the equation will also assist in the practice of the invention. In addition to the exemplary embodiments numerous other configurations will be evident for other applications. For example, the thermally conductive bodies in contact with the outermost wall surfaces of circular conduits shown in Figs. 1 and 8 may be eliminated, thereby exposing this portion of the boundary interface conduit walls. The heat transfer paths within the matrix between the spaced conduit members would still be defined in accordance with this invention by the thermally conductive bodies in the fluid flow path.

It will be noted that in Fig. 10 the length of the flow path through the matrix 85 is a little less than twice the characteristic dimension 86. In other embodiments the flow path is even smaller in relation to the characteristic dimension.

WHAT WE CLAIM IS:—

1. A heat exchange structure for transferring heat between first and second fluid media through a thermally conductive solid structure which incorporates a passageway for the first medium and a plurality of flow paths for the second medium, which paths are defined between a plurality of layers of bodies forming a matrix and whose surfaces, which form the elemental surface areas of the flow paths, are predominantly convexly curved in all directions, wherein the average length of the flow paths is not greater than 15 times the average radius of curvature of the said elemental surface areas.
2. A heat exchange structure according to claim 1, wherein the said bodies are spheres.
3. A heat exchange structure according to claim 1, wherein the matrix comprises not more than seven layers of substantially spherical bodies in the direction of flow of the second medium therethrough.
4. A heat exchange structure according to claim 1, 2 or 3, and including heat source means and blower means constructed to provide and direct a flow of the second medium to and through the flow paths at such a velocity and temperature differential with respect to the solid structure that the

heat transfer rate between the second medium and the solid structure exceeds 100 watts per square inch of the surface area of the passageway for the first medium.

5. A heat exchange structure according to claim 4, wherein the said means are constructed to provide and direct the second medium flow at such a velocity and temperature differential with respect to the solid structure that the said heat transfer rate exceeds 1000 watts per square inch of the said surface area.

6. A heat exchange structure according to claim 4 or 5, wherein the said means for providing and directing comprise means for generating the second medium as the products of combustion of a fuel.

7. A heat exchange structure according to claim 1, 2 or 3, and including a burner arranged to supply the second medium as the products of combustion of an air-gas mixture mixed before reaching the matrix of bodies.

8. A heat exchange structure according to claim 7, wherein the burner comprises a combustion chamber surrounded by the matrix of bodies.

9. A heat exchange structure according to any of claims 1 to 8, wherein the matrix is formed within a conduit around which the said passageway is provided and wherein the average length of the flow paths is less than twice the characteristic transverse dimension of the conduit.

10. A heat exchange structure according to any of claims 1 to 8, wherein the said passageway comprises a plurality of spaced portions embedded in the matrix and wherein the average length of the flow paths is less than twice the characteristic transverse dimension between the said spaced portions.

11. A heat exchanged structure according to any of claims 1 to 8 or claim 10, wherein the said passageway comprises a plurality of tubular channels through the matrix.

12. A heat exchange structure according to any of claims 1 to 8, or claim 10, wherein the said passageway comprises a helical tubular channel through the matrix.

13. A heat exchange structure according to claim 11 or 12, wherein the matrix surrounds a central plenum from which the second medium flows out substantially radially through the said flow paths.

14. A heat exchange structure according to any of claims 1 to 13, wherein the layers of bodies are bonded to each other and to at least one tubular element defining the said passageway to form a rigid matrix structure.

15. A heat exchange structure substantially

as in
and as in
and 9,
Fig. 7,

structure will now be apparent to those skilled in the art from this description. The design criteria of the number of bonded joints along the heat path and the average size of the thermally conductive bodies in relation to the characteristic dimension to provide the desired optical density have been carefully enumerated. The foregoing discussion and exemplary application of the equation will also assist in the practice of the invention. In addition to the exemplary embodiments numerous other configurations will be evident for other applications. For example, the thermally conductive bodies in contact with the outermost wall surfaces of circular conduits shown in Figs. 1 and 8 may be eliminated, thereby exposing this portion of the boundary interface conduit walls. The heat transfer paths within the matrix between the spaced conduit members would still be defined in accordance with this invention by the thermally conductive bodies in the fluid flow path.

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1. A heat exchange structure for transferring heat between first and second fluid media through a thermally conductive solid structure which incorporates a passageway for the first medium and a plurality of flow paths for the second medium, which paths are defined between a plurality of layers of bodies forming a matrix and whose surfaces, which form the elemental surface areas of the flow paths, are predominantly convexly curved in all directions, wherein the average length of the flow paths is not greater than 15 times the average radius of curvature of the said elemental surface areas.

2. A heat exchange structure according to claim 1, wherein the said bodies are spheres.

3. A heat exchange structure according to claim 1, wherein the matrix comprises not more than seven layers of substantially spherical bodies in the direction of flow of the second medium therethrough.

4. A heat exchange structure according to claim 1, 2 or 3, and including heat source means and blower means constructed to provide and direct a flow of the second medium to and through the flow paths at such a velocity and temperature differential with respect to the solid structure that the

heat transfer rate between the second medium and the solid structure exceeds 100 watts per square inch of the surface area of the passageway for the first medium.

5. A heat exchange structure according to claim 4, wherein the said means are constructed to provide and direct the second medium flow at such a velocity and temperature differential with respect to the solid structure that the said heat transfer rate exceeds 1000 watts per square inch of the said surface area.

6. A heat exchange structure according to claim 4 or 5, wherein the said means for providing and directing comprise means for generating the second medium as the products of combustion of a fuel.

7. A heat exchange structure according to claim 1, 2 or 3, and including a burner arranged to supply the second medium as the products of combustion of an air-gas mixture mixed before reaching the matrix of bodies.

8. A heat exchange structure according to claim 7, wherein the burner comprises a combustion chamber surrounded by the matrix of bodies.

9. A heat exchange structure according to any of claims 1 to 8, wherein the matrix is formed within a conduit around which the said passageway is provided and wherein the average length of the flow paths is less than twice the characteristic transverse dimension of the conduit.

10. A heat exchange structure according to any of claims 1 to 8, wherein the said passageway comprises a plurality of spaced portions embedded in the matrix and wherein the average length of the flow paths is less than twice the characteristic transverse dimension between the said spaced portions.

11. A heat exchanged structure according to any of claims 1 to 8 or claim 10, wherein the said passageway comprises a plurality of tubular channels through the matrix.

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14. A heat exchange structure according to any of claims 1 to 13, wherein the layers of bodies are bonded to each other and to at least one tubular element defining the said passageway to form a rigid matrix structure.

15. A heat exchange structure substantially

as hereinbefore
and as illustrated
and 9, or Fig. 7, of 1

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as hereinbefore described with reference to,
and as illustrated in, Figs. 1 to 3, or Figs. 8
and 9, or Figs. 10 and 11, or Figs. 12 and
Fig. 7, of the accompanying drawings.

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