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(54) **RADIANT HEAT TRANSFER SYSTEM**

WÄRMESTRAHLUNGSÜBERTRAGUNGSSYSTEM

SYSTÈME DE TRANSFERT DE CHALEUR RAYONNANTE

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Description

REFERENCE TO RELATED APPLICATIONS

BACKGROUND

[0001] Radiant heating systems are used to heat steel, ceramics or other materials, water or other liquids, and the like. Many radiant heating systems have a radiant element positioned inside a radiant source. The radiant element is used to increase the heat transfer from the combustion of a fuel to the radiant source. The radiant element may prematurely or unexpectedly fail from the temperature and/or heating cycles. The radiant element also may create hot spots and other non-uniform heat transfer locations that cause the failure of the radiant source.

[0002] Fuels are commonly burned (oxidized) to generate heat. Common fuels are fossil fuels, such as natural gas, oil, and coal, or renewable fuels, such as biomass, and the like. Once generated, the heat may be transferred to an oven to heat an object or to a fluid, such as a liquid or gas. The heat may be transferred by at least one of conduction, convection, and radiation. Conduction occurs in solids, where heat from one solid, or part of a solid, moves to another solid or part of the same solid. Convection occurs in fluids, such as water or air, where the heated fluid moves from one location to a second location. Radiation occurs when a heated object emits radiant energy that is absorbed by another object. Radiant heat transfer differs from conduction and convection in that contact with a solid, liquid, or gas is not needed to transfer the heat. See Boyer, Howard E., Practical Heat Treating, American Society for Metals, Metals Park, Ohio, 1984, pp. 60-62. For example, the sun heats the earth by transferring radiant energy through the vacuum of space.

[0003] Industrial heating processes, often referred to as process heating, include the heat treating of steel or other metal parts, immersion heating where a liquid is heated to serve as a convection heat source, and steam generation for electricity production. Some industrial heating processes isolate the burning of fuel and the associated combustion products from what is being heated by containing the burning and combustion products in an enclosure, such as a tube. The fuel and oxidant are introduced at one end of the tube or enclosure and the combustion products, such as carbon dioxide, water vapor, and nitrogen, are removed from another end of the tube or enclosure. Thus, heat is indirectly transferred to what is being heated.

[0004] FIG. 1 depicts a conventional radiant heat transfer system **100** for process heating that indirectly transfers the heat from a burning fuel **110** to a heating zone **120** contained by a furnace **130.** The radiant heat transfer system **100** may include a diffusion flame burner **105** that includes inlets for air and fuel. A more detailed description of burners used with radiant heat transfer systems may be found in R.F. Harder, R. Viskanta and S. Ramadhyani, Gas-Fired Radiant Tubes: A Review of Literature, December 1987, Gas Research Institute, for example. While not shown in the figure, the furnace **130** may include fans or other devices to circulate a gaseous atmosphere within the furnace **130.** The gaseous atmosphere my include hydrogen, nitrogen, and carbon monoxide, for example.

[0005] In the conventional radiant heat transfer system **100,** a flame **114** is formed from the burning fuel **110.** The flame **114** generally has good radiant heat transfer properties. Combustion products **115,** often referred to as products of combustion, also are formed from the burning fuel **110** and exit through outlet **142.** The combustion products **115** have poor radiant heat transfer properties in relation to the flame **114.** The combustion products **115** have an emissivity, or ability to radiate heat, typically less than 0.1. The combustion products **115** may include water vapor, carbon dioxide, and nitrogen when fossil fuels are burned. The temperature of the combustion products **115** may vary from about 260 degrees Celsius (°C) (500 degrees Fahrenheit (°F)) to about 1371°C (2500°F).

[0006] The walls of the furnace **130** may be insulated with an insulator **135,** such as firebrick and the like. The radiant heat transfer system **100** includes a radiant source **140,** such as the depicted U-tube. The tube may have any inside diameter appropriate for the application, with inside diameters from about 7.6 centimeters (cm) (3 inches (in)) to about 20 cm (8 in) being common. In addition to the heating zone **120,** the radiant source **140** may heat any surface in proximity to the radiant source **140,** such as the furnace **130,** the insulator **135,** and the like. Additional details regarding the use of U-tubes as the radiant source **140** may be found in U.S. Pat. Nos. 5,655,599; 5,071,685; and 4,789,506. In other radiant heat transfer systems, the radiant source **140** may be a straight or other shape tube or any structure that contains the burning fuel **110,** flame **114,** and the combustion products **115.**

[0007] A first portion **144** of the radiant source **140** may radiate more heat to the heating zone **120** than a second portion **146** of the radiant source **140.** The first portion 144 may radiate about 68,600 kilojoules per hour (kj/hr) [65,000 British Thermal Units per hour (BTU/hr)] and the second portion **146** may radiate about 47,500 kJ/hr (45,000 BTU/hr). Thus, the second portion **146** of the radiant source **140** may radiate about 30 percent (%) to about 45% less heat than the first portion **144.** The closer proximity of the first portion **144** to the burning fuel **110** and containing the flame **114** typically causes the first portion **144** to radiate more heat to the heating zone **120** than the second portion **146,** which contains the combustion products **115.** This uneven heat transfer from the radiant source **140** may lead to the uneven heating of objects within the furnace **130,** thus increasing costs and providing a lower quality heat treated product.

[0008] One reason for lower heat transfer in the second portion **146** of the radiant source **140** is the reduced ability of the combustion products **115,** which are mostly gaseous, to transfer heat to the walls of the radiant source **140** in relation to the burning fuel **110.** A substantial amount of heat, such as about 174,000 kJ/hr (165,000 BTU/hr), may be trapped in the combustion products **115** exiting the radiant source **140** through the outlet **142.** The heat lost in the combustion products may increase the operating costs of the radiant heat transfer system **100.**

[0009] Conventional attempts at converting this lost heat into radiant heat at the second portion **146** of the radiant source **140** are mixed. One conventional method, as disclosed in U.S. Pat. No. 4,869,230, uses a corrugated strip of metal alloy to increase the surface area for heat radiation and increase the movement of the gaseous combustion products **115** to increase their convection within the radiant source **146.** Furthermore, this increased movement of the gaseous combustion products **115,** or turbulence, may increase the burn rate of any burning fuel **110** remaining in the second portion **146** of the radiant source **140.** Turbulence may result in hot spots along the length of the radiant source **140** where temperatures may vary by up to about 150 °C (300 °F). Thus, a metal insert was used to absorb heat by convection and transfer heat through radiation.

[0010] While effective in the short term, metal inserts have the disadvantage of not being durable and have been replaced with ceramic inserts that can better withstand higher temperatures. Conventional ceramic inserts are described in U.S. Pat. Nos. 2,861,596; 4,153,035; and 6,484,795, for example. Some conventional inserts have wings extending in a radial manner outward from a solid longitudinal core, thus crossing at the center point of the core. However, while better able to withstand higher temperatures than metal, the ceramic inserts are inherently brittle, thus having the disadvantage of breaking or shattering due to the thermal cycling and vibrations occurring within the radiant heat transfer system **100** during use. Breakage of ceramic inserts may result in the destruction of the radiant source **140.** GB 1199092 discloses a radiant heating tube which comprises a flame tube into which a burner, supplied with fuel and air, projects; the flame tube including at least in part inter fitting arcuate ceramic segments.

[0011] US 3,290,383 discloses a heat exchanger for use as a recuperator for radiant tube burners which includes a fluted heat exchange surface.

[0012] US 2,226,816 discloses a heating apparatus comprising a fuel-fired radiator tube for producing radiant heat in a furnace chamber.

[0013] Accordingly, there is an ongoing need for improved radiant heating systems, especially those that may provide greater and/or more uniform heat transfer and lower costs. The systems, devices, and methods of the present invention overcome at least one of the disadvantages associated with conventional radiant heating systems.

SUMMARY

[0014] The present invention relates to a radiant heat transfer system according to claim 1.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The invention can be better understood with reference to the following drawings and description. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. Moreover, in the figures, like referenced numerals designate corresponding parts throughout the different views.

FIG. 1 depicts a conventional radiant heat transfer system for process heating that indirectly transfers heat from a burning fuel to a heating zone contained by a furnace.

FIG. 2 depicts a radiant heat transfer system with radiant elements for process heating that indirectly transfers heat from a burning fuel to a heating zone contained by a furnace.

FIGs. 3A and 3B depict axial and longitudinal cross-sectional views, respectively, of a radiant source including two radiant elements and a spacer.

FIG. 3C depicts an axial view of a retention device and positioning rod for holding a radiant element in a radiant source.

FIG. 3D depicts vertically positioned radiant elements held by a positioning rod in a radiant source.

FIGs. 4A-4D depict different views of a radiant element.

FIG. 4E depicts a perspective view of a radiant element with wings having an essentially constant pitch of about 45°.

FIG. 4F depicts a perspective view of a radiant element where the pitch each of each wing transitions from about 90° at each end to about 45° at the center.

FIG. 4G-1 and FIG. 4G-2 provide supporting calculations for Reynolds Numbers.

FIGs. 5A-5C illustrate axial cross-sections of wings tangentially attached to a longitudinal core.

FIG. 5D illustrates axial cross-sections of wings normally attached to a core section.

FIGs. 6A-6E depict perspective views of various radiant elements with wings normal to a core section.

FIG. 7 depicts a radiant heat transfer system for immersion heating that transfers the heat from a burning fuel to a fluid contained by a vessel.

FIG. 8 depicts a radiant heat transfer system for a boiler that generates steam from burning a solid fuel.

DETAILED DESCRIPTION

[0016] Radiant elements convert the combustion products from burning fuel into radiant energy. A radiant element may be formed from one or more ceramics and may be used in radiant sources, such as radiant tubes, immersion tubes, heat exchanger tubes, boiler walls, and other radiant heat applications. Each radiant element has a core section defining a longitudinal cavity. The longitudinal cavity enables the insertion of a positioning mechanism that can be used to control the location of the radiant element in a radiant source. Each radiant element may have one or more normal and/or tangential wings attached to the exterior of the core section. The wings may produce a more laminar (or less turbulent) flow of the combustion products within the radiant source. The more laminar flow may improve the heat transfer from the combustion products to the radiant element, thus improving the heat transfer from the combustion products to the radiant source. The more laminar flow decreases the turbulence that may cause failure of the radiant element and/or radiant source.

[0017] FIG. 2 depicts a radiant heat transfer system **200** for process heating that indirectly transfers heat from a burning fuel **210** and flame **214** to a heating zone **220** contained by a furnace **230.** The radiant heat transfer system **200** includes a radiant source **240,** having a first portion **244** and a second portion **246.** Unlike the convention radiant heat transfer system **100** of FIG. 1, the radiant heat transfer system **200** of FIG. 2 includes at least one radiant element **260** inserted in the second portion **246** of the radiant source **240.** The radiant heat transfer system **200** has a burner **205** connected to the first portion **244** of the radiant source **240.** The first portion **244** is where most or all of the fuel is combusted in the radiant source **240.** The second portion **246** is where the combustion gases flow prior to exiting the radiant source **240.** While three of the radiant elements **260** are depicted in FIG. 2, one or more radiant elements may be placed in the second portion **246** of the radiant source **240.** Furthermore, the radiant element **260** may be a single element that occupies part, substantially all, or the entire longitudinal length of the second portion **246** of the radiant source **240.** Preferably, the one or more radiant elements **260** occupy greater than about 50% of the longitudinal length of the second portion **246** of the radiant source **240.** More preferably, the one or more radiant elements **260** occupy from about 70% to about 80% of the longitudinal length of the second portion **246** of the radiant source **240.**

[0018] The radiant element **260** may be formed from any ceramic; preferably a ceramic having greater resistance to the thermal stresses within the radiant heat transfer system **200.** Ceramics include true ceramics and ceramic-like materials that include additional materials, such as metals. The radiant element **260** may be formed from a powder, including silicon carbide and silicon combined with a binder that is heated at a temperature to fuse the powder into a desired ceramic structure. Thus, the fired ceramic may be a siliconized silicon carbide. Other materials may be used in forming the ceramic, such as silicon nitride, silicon-mullite, alumina, and the like. Preferably, the ceramic from which the radiant element **260** is formed has an emissivity of greater than about 0.4, preferably from about 0.4 to about 0.9. Good emissivity performance of the material from which the radiant element **260** is formed reduces fuel consumption.

[0019] As the burning fuel **210** forms combustion products and a flame **214,** a nearly complete combustion zone **250** may form. In the nearly complete combustion zone **250,** the burning fuel **210** is at least about 80% to about 85% converted to the combustion products **215.** Preferably, at least about 90% of the burning fuel **210** may be converted to the combustion products **215** in the nearly complete combustion zone **250.** Any remaining uncombusted fuel is combusted after the nearly complete combustion zone in the radiant source **240.**

[0020] The radiant element **260** may be placed after the nearly complete combustion zone **250.** The radiant element **260** may be placed in the combustion zone **250** where about 90% of the burning fuel **210** has been converted to the combustion products **215.** If the radiant element **260** is placed too close to the burning fuel **210,** the radiant element may fail. A similar failure may occur if the radiant element **260** is placed in an insulated portion of the radiant source **240.** If the radiant element **260** is placed too far from the nearly complete combustion zone **250,** the ability of the radiant element **260** to convert the heat trapped in the combustion products **215** to radiant energy may be reduced. Thus, appropriate positioning of the radiant element or elements **260** in the radiant source **240** is preferred.

[0021] If the radiant element **260** fills too much of the axial cross-sectional area of the radiant source **240,** the turbulence and/or back pressure of the combustion products **215** may increase to the point where the radiant element **260** and/or the radiant source **240** fail. The radiant element **260** occupies less than about 20%, preferably from about 5% to about 10%, of the axial cross-sectional area of the radiant source **240.** Similarly, if the radiant element **260** does not sufficiently direct the flow of the combustion products **215,** the heat of the combustion products **215** may not be effectively converted to radiant energy. Thus, it is desired for the radiant element **260** to radiate heat from the combustion products **215** while not creating more turbulence in the flow of the combustion products **215** that may cause mechanical failure of the radiant element **260** or the radiant source **240.**

[0022] By converting a portion of the heat within the combustion products **215** into radiant energy, the radiant element **260** may improve the uniformity of heat transfer from the first and second portions **244, 246** of the radiant source **240** and may increase the radiant heat transferred from the burning fuel **210** to the heating zone **220.** For example, about 174,000 kj/hr (165,000 BTU/hr) of heat is lost through the outlet **142** of the conventional radiant heat transfer system **100** of FIG. 1. In the radiant heat transfer system **200** of FIG. 2, the radiant element **260** may recover about 15,800 kj/hr (15,000 BTU/hr) from the combustion products **215** and radiate it to the second portion **246** of the radiant source **240.** Thus, the approximate 21,100 kj/hr (20,000 BTU/hr) difference between the first and second portions **144, 146** of the radiant source **140** of FIG. 1 may be reduced to a 5,300 kj/hr (5,000 BTU/hr) difference in FIG. 2 with the radiant element **260.**

[0023] FIG. 3A depicts an axial cross-section of a radiant source **340.** FIG. 3B depicts a longitudinal cross-section of two radiant elements **360** positioned within the radiant source **340.** Each radiant element **360** includes a central longitudinal core section **370.** The interior of the core section **370** defines a longitudinal cavity **375.** The exterior of the core section **370** defines an exterior **372** that attaches at least one wing **390.** Terminal surfaces **392** are farthest from the longitudinal core section **370** in an axial direction and may or may not contact the interior wall of the radiant source **340.** The shape of the terminal surfaces **392** may provide for better positioning accuracy of the radiant element **360** including when contacting the inner wall of the radiant source **340** or in relation to additional radiant elements. Due to the increased surface area of the radiant element **360** in relation to a tube of equivalent axial diameter, the radiant element **360** may provide a greater heat emissivity than a circular tube of the same outside diameter and length. The radiant element **360** has an element surface area, which is the surface area of all the radiant elements in the radiant source **340.** The radiant source **340** has a source surface area, which is the surface area of the interior wall of the radiant source facing the radiant element **360** or corresponding to the length the radiant element **360.** The ratio of the element surface area to the source surface area is greater than about 1.1:1. The ratio of the element surface area to the source surface area may be from about 1.1:1 to about 3:1. The ratio of the element surface area to the source surface area may be from about 1.2:1 to about 1.5:1. Other ratios of the surface areas may be used. In this manner, the radiant element **360** may increase energy adsorption and radiation, thus increasing heat transfer to the radiant source **340.**

[0024] The cavity **375** may be accessible from each longitudinal end of the radiant element **360.** While depicted as an essentially circular tube in FIG. 3B, the cavity **375** may be any shape, such as spherical, triangular, polygonal, rectangular, elliptical, combinations of these or other shapes, and the like. The cavity **375** may vary in size and shape along the longitudinal length of the radiant element **360.** Thus, the axial cross-section of the cavity **375** may be symmetrical or asymmetrical along the longitudinal axis of the radiant element **360.** The cavity **375** has a diameter of at least about 0.635 cm (0.25 in), preferably from about 1.27 cm (0.5 in) to about 1.91 cm (0.75 in). In another aspect, the thickness of the core section **370** between the cavity **375** and the exterior **372** is at least about 0.317 cm (0.125 in), preferably from 0.635 cm (0.25 in) to about 1.27 cm (0.5 in). Other cavity diameters and core thicknesses may be used.

[0025] A positioning mechanism is used to control the location of the radiant element **360** in the radiant source **340.** The positioning mechanism includes a position rod **380,** a stop device **386,** and a retention device **387.** The positioning rod **380** is disposed in the longitudinal cavity **375** of one or more radiant elements **360.** By passing the rod **380** through the cavity **375,** the radiant elements **360** may be held. The rod **380** may be made of steel, ceramic, intermetallic, a combination thereof, or like material. The rod **380** may enter a first end, extend the length of, and exit through a second end of the cavity **375.** When more than one radiant element **360** occupies the rod **380,** a spacer **382** of sufficient outside diameter to prevent the core sections **370** of the radiant elements **360** from contacting may be placed over the rod **380.** The spacer may be from about 2.5 cm (1 in) to 32 cm (12.5 in) in length. The spacer length may be selected in response to the inside diameter of the radiant source **340.** Other spacer lengths may be used. In addition to containing a portion of the rod **380,** the cavity **375** may provide for the injection of a fluid, such as a gas other than a fuel gas, into the radiant element **360.**

[0026] At a first end **384,** the rod **380** may be provided with a stop device **386** sufficient to prevent the core section **370** from sliding past the first end **384** of the rod **380.** The first end **384** of the rod **380** may be threaded. A washer and bolt or a washer and a nut may be placed on the rod **380** to prevent the radiant element **360** from sliding past the first end **384** of the rod **380.** The stop device **386** may be provided by bending the first end **384** of the rod **380** to prevent the radiant element 360 from sliding. Other stop devices may be used to prevent the radiant element 360 from sliding off of the rod **380.**

[0027] In FIG. 3C, the rod **380** may have a retention device **387** at a second end **388.** The retention device **387** may be one or more cross pieces, a cap, a metal bar, or the like that fixes or connects the rod **380** to the radiant source **340.** The second end **388** of the rod **380** may be bent or equipped with a washer and/or nut **389** to hold the rod **380** in the retention device **387.** The retention device **387** may include any apparatus that fixes the rod **380** in relation to the radiant source **340.** Thus, the rod **380** may locate the radiant element **360** at a particular place or with a particular orientation within the radiant source **340.**

[0028] If the radiant elements **360** are positioned horizontally in the radiant source **340,** the rod **380** may include sufficient radiant elements and/or spacers to place a compressive force on the radiant elements **360.** For example, by tightening the bolts at the first and second ends **384, 388** of the rod **380,** the radiant element or elements **360** may be held in compression. This horizontal compressive force applied by tightening the bolts may overcome the tension force being vertically applied to the radiant elements **360** by gravity.

[0029] In FIG. 3D, the radiant elements **360** are positioned vertically in the radiant source **340.** In a vertical position, the radiant elements **360** may be placed under compressive force without filling the rod **380** with spacers and radiant elements. In this aspect, by holding the rod **380** at the top of the radiant source **340** with the retention device **387** and by holding the radiant element or elements **360** onto the rod **380** with the stop device **386,** gravity maintains a compressive force on the radiant elements **360.**

[0030] The radiant element or elements **360** in FIG. 3D are held in compression as opposed to being under tension. The ceramic, from which the radiant element **360** is formed, has excellent mechanical strength when held under compression, but have poor mechanical strength when placed under tension. As previously described, conventional ceramic inserts often fail due to vibration and thermal shock. Thus, by holding the radiant element **360** in compression, whether it resides vertically or horizontally within the radiant source **340,** the need for a ceramic material that resists thermal and/or mechanical shock may be reduced. By holding the radiant element **360** in compression, the failure rate of the element may be reduced.

[0031] FIGs. 4A-4D depict different views of a radiant element **460.** FIG. 4E depicts a perspective view of a radiant element with wings having an essentially constant pitch of about 45°. FIG. 4F depicts perspective views of a radiant element where the pitch of each wing transitions from about 90° at each end to about 45° at the center. Combustion products may pass across the radiant element **460** in a laminar or turbulent manner. The radiant element **460** may have a surface area geometry that directs combustion products in a more laminar or less turbulent flow over the surface while radiating heat absorbed from the combustion products. Preferably, the flow of the combustion products over the radiant element **460** is a laminar or nearly laminar flow. The lower turbulence levels provided by the radiant element **460** in relation to conventional ceramic inserts may allow for increased heat radiation while avoiding the hot spots and other disadvantages of turbulent flow that may lead to failure.

[0032] A Reynolds Number (Re) describes whether a flow is laminar, turbulent, transitional, or a mixed. For example, in tubes, a Re below 2300 is considered laminar while a Re above 4500 is considered turbulent. A Re between 2300 and 4500 is considered transitional or mixed. Thus, a lower Reynolds Number indicates a more laminar flow. As a further example, combustion products moving through a radiant tube with an inside diameter of 10.16 cm (4 in) have a Re of 3742, thus being transitional or more turbulent than laminar. In comparison, combustion products flowing past a radiant element with three wings in a radiant tube with an inside diameter of about 10.16 cm (4 in) have a Re of 1914, which is laminar flow. The supporting calculations for these Reynolds Numbers are shown in FIG. 4G-1 and FIG. 4G-2. These calculations are for a radiant element with three wings and show the Reynolds Number calculated for flow between two of the wings. Tubes with other Reynolds Numbers indicating laminar, turbulent, or mixed flow may be used. Thus, the radiant elements of the present invention may significantly increase the laminar flow of combustion products through a radiant source. The radiant elements may provide a Re below 2300, more preferably from 1500 to 2300 for combustion products flowing through a radiant source. The radiant elements may provide flows of the combustion products with other Reynolds Numbers.

[0033] As depicted in the FIG. 4A perspective and the FIG. 4D axial cross-section, the radiant element **460** includes a central longitudinal core section **470** defining a longitudinal cavity **475** and an exterior **472** attaching to three wings **490.** The wings **490** may be attached to the exterior **472** in a normal, tangential, a combination these, or another geometry in relation to the exterior **472** or outside surface of the core section **470.** Preferably, the wings **490** are attached in a normal, tangential, or in a combination of these geometries. More preferably, the wings **490** are attached in a tangential geometry.

[0034] The wings **490** may increase the surface area of the radiant element 460. While the radiant element **460** is depicted with three wings, one or more wings may be used. If the radiant element **460** includes greater than four wings, the resulting decrease in the open cross-sectional area of the radiant source may result in an undesirable drop in the flow velocity of the combustion products. The core section **470** may have portions with and without the wings **490.**

[0035] FIG. 4B depicts wings **490** having a helical shape with a pitch angle of about 45°. The pitch angle of the wings **490** is the orientation of the wings in relation to the center axis of the radiant element **460** or in relation to the axis of the core section **470.** Pitch angles from about 20° to about 90° are preferred, with angles from about 30° to about 60° being more preferred. Other pitch angles may be used. The pitch angles of the wings **490** may remain constant or may vary along the longitudinal length of the radiant element **460.** For example, FIG. 4E depicts a perspective view of the radiant element **460** with wings having an essentially constant pitch of about 45°. In contrast, FIG. 4F depicts a perspective view of a radiant element where the wing pitch transitions from about 90° at each end to about 45° at the center or middle of the radiant element. The smooth transition between the about 45° pitch angle at the center and the about 90° pitch angle at the ends may provide for reduced turbulence in relation to designs having stepped transitions between angles.

[0036] FIG. 4C is a longitudinal cross-section of the radiant element **460.** FIG. 4D illustrates that the wings **490** may be thicker where attached to the exterior **472** than at a terminus **492.** Thus, the wings **490** may have a non-uniform thickness and taper from the exterior **472** to the terminus **492.** For one or more of the wings, the ratio of the height of the wing (the distance from the exterior **472** to the terminus **492**) to the diameter of the core section **470** may be greater than about 4:1. The ratio of the height of the wing to the diameter of the core section may be from about 4:1 to about 50:1. The ratio of the height of the wing to the diameter of the core section may be from about 5:1 to about 11:1. Other ratios of the height of the wing to the diameter of the core section may be used.

[0037] FIGs. 5A-5C illustrate axial cross-sections of wings **590** tangential to a central longitudinal core section **570.** In FIG. 5A the wings **590** are straight and are tangential with a circle **593** representing the exterior of the central longitudinal core section **570.** In this illustration, the angle of the wings **590** to the circle **593** is about 0°. In FIG. 5B, the wings **590** also are tangential to the circle **593,** but are curvilinear in shape. Unlike the straight wings of FIG. 5A, the curvilinear wings of FIG. 5B would not lay flat on a table if removed from the core section **570.** Thus, the terminus of a curvilinear wing does not align with the portion of the wing attached to the central longitudinal core section **570.** In FIG. 5C the central longitudinal core section **570** is triangular in shape, thus allowing the curvilinear wings to be tangential to the central point **593** of the core section **570.** In contrast to FIGs. 5A-5C, the wings **590** of FIG. 5D are not tangential, but normal (nearly 90°) to the longitudinal core section **570.**

[0038] FIGs. 6A-6E depict perspective views of various radiant elements with wings **690** normal to the exterior **694** or outside surface of a longitudinal core section **670.** In FIG. 6A the approximately 90° normal attachment of the wings **690** is seen at the top of the radiant element. FIG. 6B depicts curvilinear wings **690** also having an approximately 90° normal attachment to the longitudinal core section **670.** FIG. 6C depicts wings **690** normal to a longitudinal core section **670,** but where the wings **690** transition from an about 90° pitch at either end to an about 45° pitch in the central region. FIG. 6D depicts wings **692** that extend farther from the longitudinal core section **670** than wings **691,** thus establishing that a radiant element may include wings of different heights. FIG. 6E depicts a radiant element having normal to the center point **694** wing attachment, but where the wings **690** have a complex curvilinear shape.

[0039] FIG. 7 depicts a radiant heat transfer system **700** for indirect immersion heating that transfers heat from a burning fuel **710** to a fluid **720** contained by a vessel **730.** The fluid **720** may be a liquid, such as water, oil, salt solution, or the like. The radiant heat transfer system **700** includes a radiant source **740,** having an exhaust portion **746.** The exhaust portion **746** includes at least one radiant element **760.** While multiple of the radiant elements **760** are depicted in FIG. 7, one or more may be placed in the exhaust portion **746** of the radiant source **740.** Furthermore, the radiant element **760** may be a single element that occupies part, substantially all, or the entire longitudinal length of the exhaust portion. Preferably, the one or more radiant elements **760** occupy from about half to all of the longitudinal length of the exhaust portion **746** of the radiant source **740.**

[0040] FIG. 8 depicts a radiant heat transfer system **800** for a biomass or other boiler that generates steam in tubes **820** from a bed of solid burning fuel **810,** such as coal or biomass. Air may be introduced from below the burning fuel **810,** for example. Radiant element **860** is held on positioning rod **880** above the burning fuel **810.** Preferably, the multiple radiant elements **860** are held in compression above the burning fuel **810.** Combustion products **815** flow from the burning fuel **810** over the radiant elements **860.** The radiant elements **860** adsorb heat from the combustion products **815** and radiate the energy to the steam tubes **820.**

[0041] The following definitions are included to provide a clear and consistent understanding of the specification and claims.

[0042] The term "emissivity" or "emissivities" is defined as the relative power of a surface to emit heat by radiation, which may be expressed as the ratio of the radiant energy emitted by a surface to the radiant energy emitted by a blackbody (an ideal surface that absorbs all radiant energy without reflection) at the same temperature. Thus, the ability of a first material to transfer heat to a second material. *See* Webster's New Collegiate Dictionary, G. & C. Merriam Company, Springfield, Massachusetts, 1977, pp. 115, 372.

[0043] The term "compressive" or "compression" refers to the act or action of squeezing together.

[0044] The term "tension" refers to the act or action of stretching.

[0045] The term "laminar" in relation to the flow of combustion products refers to the flow condition when the individual particles move in a regular or steady motion resulting in a smooth flow line or path. The particles passing through a given point follow the same path. See Pritchard, R. et al., Handbook of Industrial Gas Utilization, Van Nostrand Reinhold Company, New York, 1977, pp. 30-31.

[0046] The term "turbulent" in relation to the flow of combustion products refers to the flow condition when the individual particles move in an irregular or unsteady motion resulting in an uneven flow line or path. The transition from laminar flow to turbulent flow occurs when the fluid velocity or speed exceeds a critical value. See Pritchard, R. et al., Handbook of Industrial Gas Utilization, Van Nostrand Reinhold Company, New York, 1977, pp. 30-31.

[0047] The term "radial" refers to a wing extending outward along a radius from a centerpoint of a radiant element.

[0048] The term "normal" refers to a wing extending at a perpendicular or nearly 90° angle from a surface, such as the exterior of the longitudinal core of a radiant element. A "normal" wing also may be "radial" if the wing extends outward along a radius from a centerpoint of a radiant element.

[0049] The term "tangential" refers to a wing extending at an angle other than 90° from a surface, such as the exterior of the longitudinal core of a radiant element.

[0050] While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that other embodiments and implementations are possible within the scope of the invention. Accordingly, the invention is not to be restricted except in light of the attached claims and their equivalents.

Claims

1. A radiant heat transfer system (200, 700), comprising a radiant source (240, 340) and at least one ceramic radiant element (260, 360, 460, 760) inside the radiant source (240, 340, 740), wherein the at least one ceramic radiant element (260, 360, 460, 760) has at least one wing (390, 490, 590, 690) extending from a core section (370, 470, 570, 670), where the core section (370, 470, 570, 670) forms a longitudinal cavity (375, 475), **characterized in that** the system further comprises a positioning mechanism disposed in the longitudinal cavity (375, 475), where the positioning mechanism is connected to the radiant source (240, 340, 740).

2. The radiant heat transfer system (200, 700) of claim 1, where the positioning mechanism comprises:

a positioning rod (380) disposed in the longitudinal cavity (375);
a stop device (386) connected to one end (384) of the positioning rod (380); and
a retention device (387) connected to the other end (388) of the positioning rod (380).

3. The radiant heat transfer system (200, 700) of claim 1 or 2, where the ceramic radiant element (260, 360, 460, 760) occupies less than about 20% of an axial cross-sectional area of the radiant source (240, 340, 740), or where the ceramic radiant element (260, 360, 460, 760) occupies from about 5% to about 10% of an axial cross-sectional area of the radiant source (240, 340, 740).

4. The radiant heat transfer system (200, 700) of claim 1 through 3, where a ratio of a ceramic radiant element (260, 360, 460, 760) surface area to a radiant source (240, 340, 740) surface area is greater than about 1.1:1, preferably about 1.1:1 to about 3:1, or more preferably about 1.2:1 to about 1.5:1.

5. The radiant heat transfer system (200, 700) of any one of claims 1 through 4, where the flow of combustion products in the radiant source (240, 340, 740) has a Reynolds Number less than about 4500, preferably less than about 2300, or more preferably of about 1500 to about 2300.

6. The radiant heat transfer system (200, 700) of any one of the preceding claims, where the at least one wing (390, 490, 590, 690) has a substantially helical shape defining a helix angle.

7. The radiant heat transfer system (200, 700) of claim 6, where the helix angle is essentially constant.

8. The radiant heat transfer system (200, 700) of claim 6 or 7, where the helix angle is from about 20° to about 90°, preferably from about 30° to about 60°, more preferably about 45°or about 90°.

9. The radiant heat transfer system (200, 700) of any one of claims 6 through 8, where the helical shape transitions from one helical angle to another helical angle.

10. The radiant heat transfer system (200, 700) of any one of the preceding claims, where a ratio of a height of the wing (390, 490, 590, 690) to a diameter of the core section (370, 470, 570, 670) is greater than about 4:1, preferably from about 4:1 to about 50:1, or more preferably from about 5:1 to about 11:1.

11. The radiant heat transfer system (200, 700) of any one of the preceding claims, where the at least one wing (390, 490, 590, 690) has a substantially curvilinear shape.

12. The radiant heat transfer system (200, 700) of any one of the preceding claims, where the at least one wing (390, 490, 590, 690) has a substantially constant height.

13. The radiant heat transfer system (200, 700) of any one of the preceding claims having an emissivity greater than about 0.4, preferably from about 0.4 to about 0.9.

14. The radiant heat transfer system (200, 700) of any one of the preceding claims, where the at least one wing (390, 490, 590, 690) is normal, tangential, or a combination thereof to the core section (370, 470, 570, 670).

Patentansprüche

1. Wärmestrahlungsübertragungssystem (200, 700), das eine Strahlungsquelle (240, 340) und mindestens ein keramisches Strahlungselement (260, 360, 460, 760) innerhalb der Strahlungsquelle (240, 340, 740) umfasst, wobei das mindestens eine keramische Strahlungselement (260, 360, 460, 760) mindestens einen Flügel (390, 490, 590, 690) aufweist, der sich von einem Kernabschnitt (370, 470, 570, 670) erstreckt, wobei der Kernabschnitt (370, 470, 570, 670) einen länglichen Hohlraum (375, 475) bildet, **dadurch gekennzeichnet, dass** das System ferner einen Positionierungsmechanismus umfasst, der in dem länglichen Hohlraum (375, 475) angeordnet ist, wobei der Positionierungsmechanismus mit der Strahlungsquelle (240, 340, 740) verbunden ist.

2. Wärmestrahlungsübertragungssystem (200, 700) nach Anspruch 1, wobei der Positionierungsmechanismus Folgendes umfasst:

eine Positionierungsstange (380), die in dem länglichen Hohlraum (375) angeordnet ist;
eine Stoppvorrichtung (386), die mit einem Ende (384) der Positionierungsstange (380) verbunden ist; und
eine Rückhaltevorrichtung (387), die mit dem anderen Ende (388) der Positionierungsstange (380) verbunden ist.

3. Wärmestrahlungsübertragungssystem (200, 700) nach Anspruch 1 oder 2, wobei das keramische Strahlungselement (260, 360, 460, 760) weniger als etwa 20 % einer axialen Querschnittsfläche der Strahlungsquelle (240, 340, 740) einnimmt oder wobei das keramische Strahlungselement (260, 360, 460, 760) etwa 5 % bis etwa 10 % einer axialen Querschnittsfläche der Strahlungsquelle (240, 340, 740) einnimmt.

4. Wärmestrahlungsübertragungssystem (200, 700) nach Anspruch 1 bis 3, wobei ein Verhältnis der Fläche eines keramischen Strahlungselements (260, 360, 460, 760) zu einer Strahlungsquelle (240, 340, 740) größer ist als etwa 1,1:1, bevorzugt etwa 1,1:1 bis etwa 3:1 oder bevorzugter etwa 1,2:1 bis etwa 1,5:1.

5. Wärmestrahlungsübertragungssystem (200, 700) nach einem der Ansprüche 1 bis 4, wobei der Fluss von Verbrennungsprodukten in der Strahlungsquelle (240, 340, 740) eine Reynolds-Zahl von weniger als etwa 4500, vorzugsweise weniger als etwa 2300 oder bevorzugter von etwa 1500 bis etwa 2300 aufweist.

6. Wärmestrahlungsübertragungssystem (200, 700) nach einem der vorhergehenden Ansprüche, wobei der mindestens eine Flügel (390, 490, 590, 690) eine im Wesentlichen schraubenförmige Form aufweist, die einen Schrägungswinkel definiert.

7. Wärmestrahlungsübertragungssystem (200, 700) nach Anspruch 6, wobei der Helixwinkel im Wesentlichen konstant ist.

8. Wärmestrahlungsübertragungssystem (200, 700) nach Anspruch 6 oder 7, wobei der Steigungswinkel von etwa 20 ° bis etwa 90 °, vorzugsweise von etwa 30 ° bis etwa 60 °, mehr bevorzugt etwa 45 ° oder etwa 90 ° beträgt.

9. Wärmestrahlungsübertragungssystem (200, 700) nach einem der Ansprüche 6 bis 8, wobei die helikale Form von einem Spiralwinkel zu einem anderen Spiralwinkel übergeht.

10. Wärmestrahlungsübertragungssystem (200, 700) nach einem der vorhergehenden Ansprüche, wobei ein Verhältnis einer Höhe des Flügels (390, 490, 590, 690) zu einem Durchmesser des Kernabschnitts (370, 470, 570, 670) größer als etwa 4:1, vorzugsweise von etwa 4:1 bis etwa 50:1 oder bevorzugter von etwa 5:1 bis etwa 11:1 ist.

11. Wärmestrahlungsübertragungssystem (200, 700) nach einem der vorhergehenden Ansprüche, wobei der mindestens eine Flügel (390, 490, 590, 690) eine im Wesentlichen kurvenförmige Form aufweist.

12. Wärmestrahlungsübertragungssystem (200, 700) nach einem der vorhergehenden Ansprüche, wobei der mindestens eine Flügel (390, 490, 590, 690) eine im Wesentlichen konstante Höhe aufweist.

13. Strahlungswärmeübertragungssystem (200, 700) nach einem der vorhergehenden Ansprüche, das ein Emissionsvermögen von mehr als etwa 0,4, vorzugsweise von etwa 0,4 bis etwa 0,9 aufweist.

14. Wärmestrahlungsübertragungssystem (200, 700) nach einem der vorhergehenden Ansprüche, wobei der mindestens eine Flügel (390, 490, 590, 690) senkrecht, tangential oder in einer Kombination davon zu dem Kernabschnitt (370, 470, 570, 670) angeordnet ist.

Revendications

1. Système de transfert de chaleur rayonnante (200, 700), comprenant une source rayonnante (240, 340) et au moins un élément rayonnant en céramique (260, 360, 460, 760) à l'intérieur de la source rayonnante (240, 340, 740), l'au moins un élément rayonnant en céramique (260, 360, 460, 760) ayant au moins une aile (390, 490, 590, 690) qui s'étend à partir d'une section centrale (370, 470, 570, 670), où la section centrale (370, 470, 570, 670) forme une cavité longitudinale (375, 475), **caractérisé en ce**

que le système comprend en outre un mécanisme de positionnement disposé dans la cavité longitudinale (375, 475), où le mécanisme de positionnement est raccordé à la source rayonnante (240, 340, 740) .

2. Système de transfert de chaleur rayonnante (200, 700) de la revendication 1, où le mécanisme de positionnement comprend :

une broche de positionnement (380) disposée dans la cavité longitudinale (375) ;
un dispositif d'arrêt (386) raccordé à une extrémité (384) de la broche de positionnement (380) ; et
un dispositif de retenue (387) raccordé à l'autre extrémité (388) de la broche de positionnement (380).

3. Système de transfert de chaleur rayonnante (200, 700) de la revendication 1 ou 2, où l'élément rayonnant en céramique (260, 360, 460, 760) occupe moins de 20 % environ d'une aire axiale en coupe transversale de la source rayonnante (240, 340, 740), ou où l'élément rayonnant en céramique (260, 360, 460, 760) occupe de 5 % environ à 10 % environ, d'une aire axiale en coupe transversale de la source rayonnante (240, 340, 740).

4. Système de transfert de chaleur rayonnante (200, 700) de la revendication 1 à 3, où un rapport entre une superficie d'élément rayonnant en céramique (260, 360, 460, 760) et une superficie de source rayonnante (240, 340, 740) est plus grande que 1,1:1 environ, de préférence de 1,1:1 environ à 3:1 environ, ou de plus grande préférence de 1,2:1 environ à 1,5:1 environ.

5. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications 1 à 4, où le flux des produits de combustion dans la source rayonnante (240, 340, 740) a un nombre de Reynolds qui est plus petit que 4500 environ, de préférence plus petit que 2300 environ, ou de plus grande préférence de 1500 environ à 2300 environ.

6. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications précédentes, où l'au moins une aile (390, 490, 590, 690) a une forme substantiellement hélicoïdale définissant un angle d'hélice.

7. Système de transfert de chaleur rayonnante (200, 700) de la revendication 6, où l'angle d'hélice est essentiellement constant.

8. Système de transfert de chaleur rayonnante (200, 700) de la revendication 6 ou 7, où l'angle d'hélice est de 20° environ à 90° environ, de préférence de 30° environ à 60° environ, de plus grande préférence de 45° environ à 90° environ.

9. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications 6 à 8, où la forme hélicoïdale passe d'un angle hélicoïdal à un autre angle hélicoïdal.

10. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications précédentes, où un rapport entre une hauteur de l'aile (390, 490, 590, 690) et un diamètre de la section centrale (370, 470, 570, 670) est plus grand que 4:1 environ, de préférence de 4:1 environ à 50:1 environ, ou de plus grande préférence de 5:1 environ à 11:1 environ.

11. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications précédentes, où l'au moins une aile (390, 490, 590, 690) a une forme substantiellement curviligne.

12. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications précédentes, où l'au moins une aile (390, 490, 590, 690) a une hauteur substantiellement constante.

13. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications précédentes ayant une émissivité qui est plus grande que 0,4 environ, de préférence de 0,4 environ à 0,9 environ.

14. Système de transfert de chaleur rayonnante (200, 700) de l'une quelconque des revendications précédentes, où l'au moins une aile (390, 490, 590, 690) est perpendiculaire, tangentielle, ou une combinaison de ces positions, à la section centrale (370, 470, 570, 670).

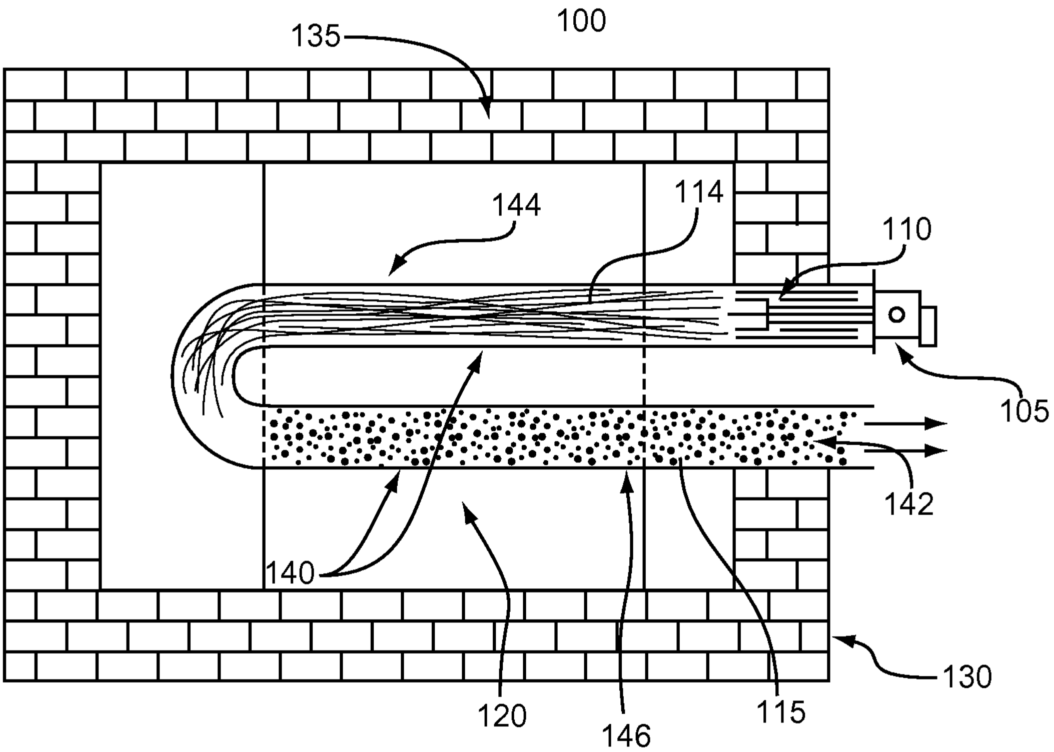
100
135
144
114
110
105
142
140
120
146
115
130

Fig.1

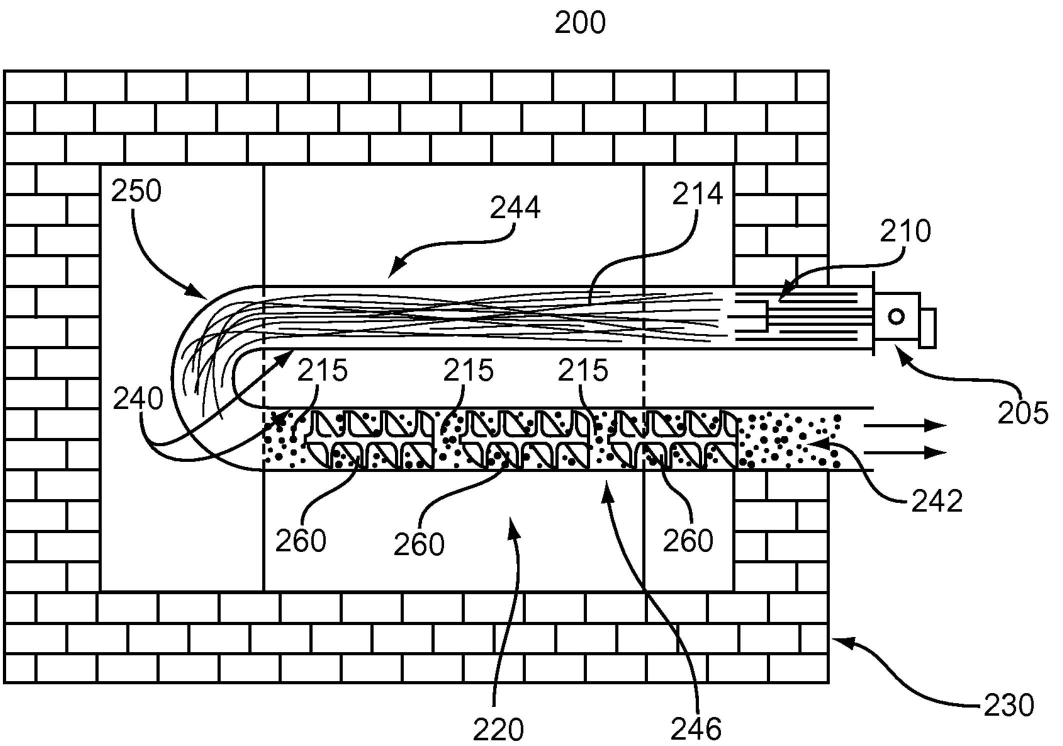
200
250
244
214
210
205
215
215
215
240
242
260
260
260
220
246
230

Fig.2

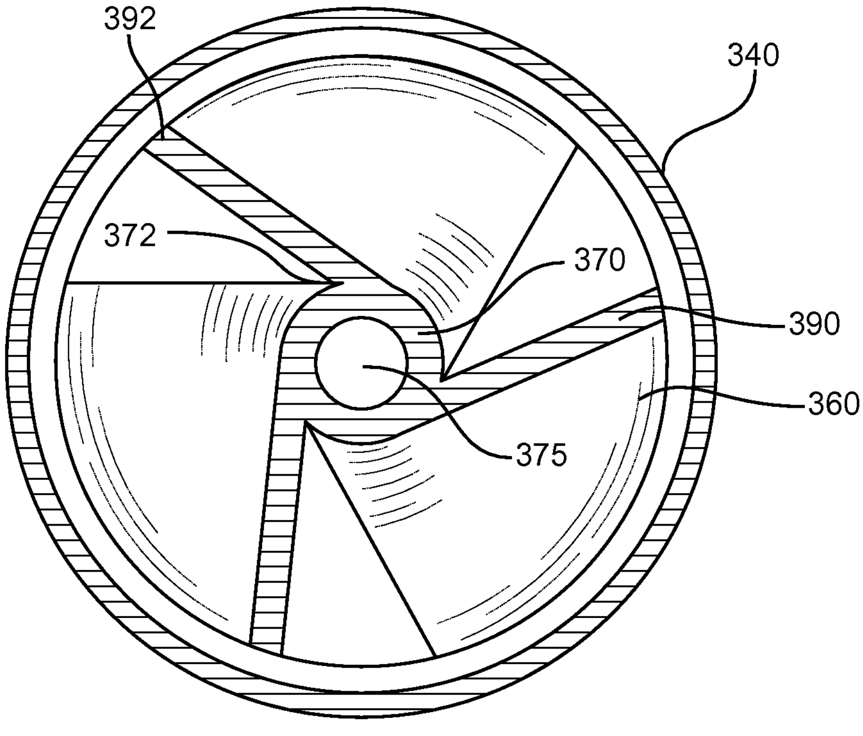
392
340
372
370
390
360
375

Fig.3A

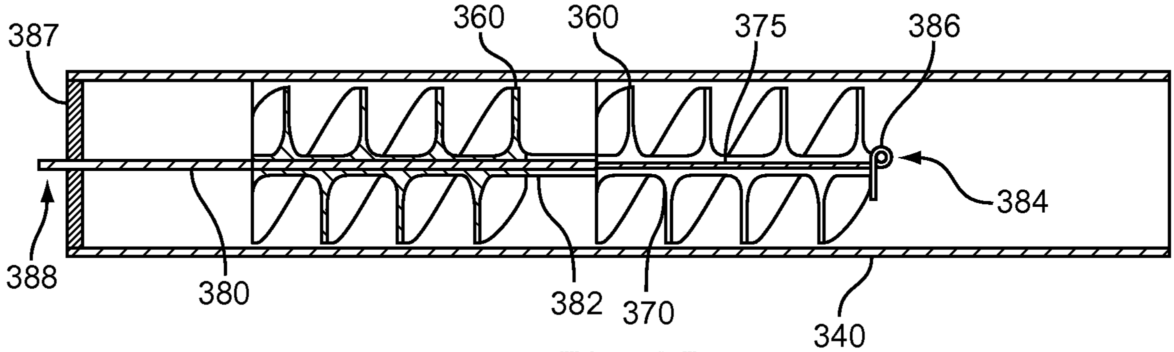
387
360
360
375
386
384
388
380
382
370
340

Fig.3B

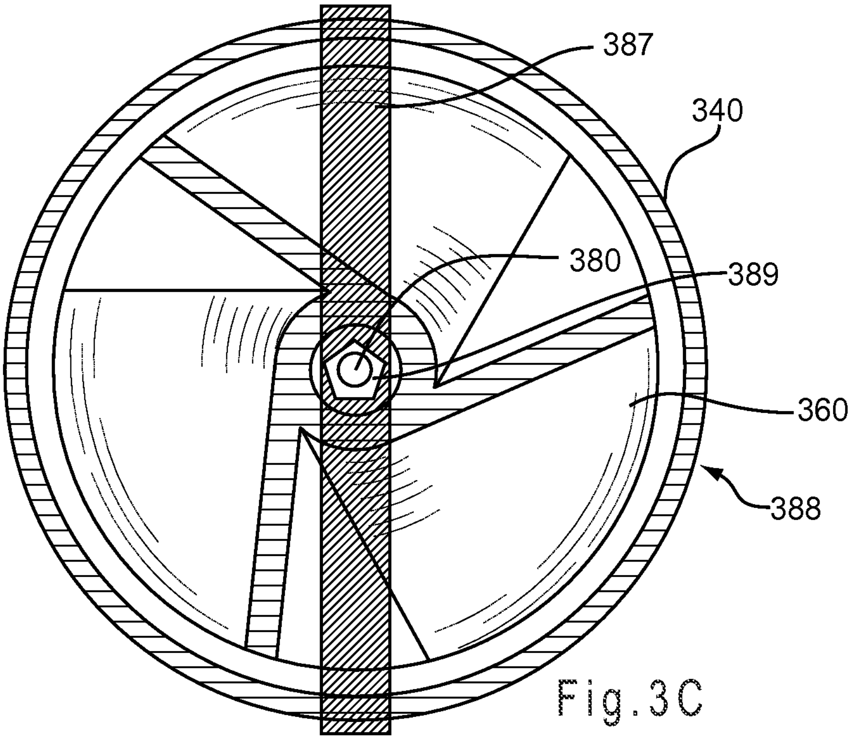

Fig.3C

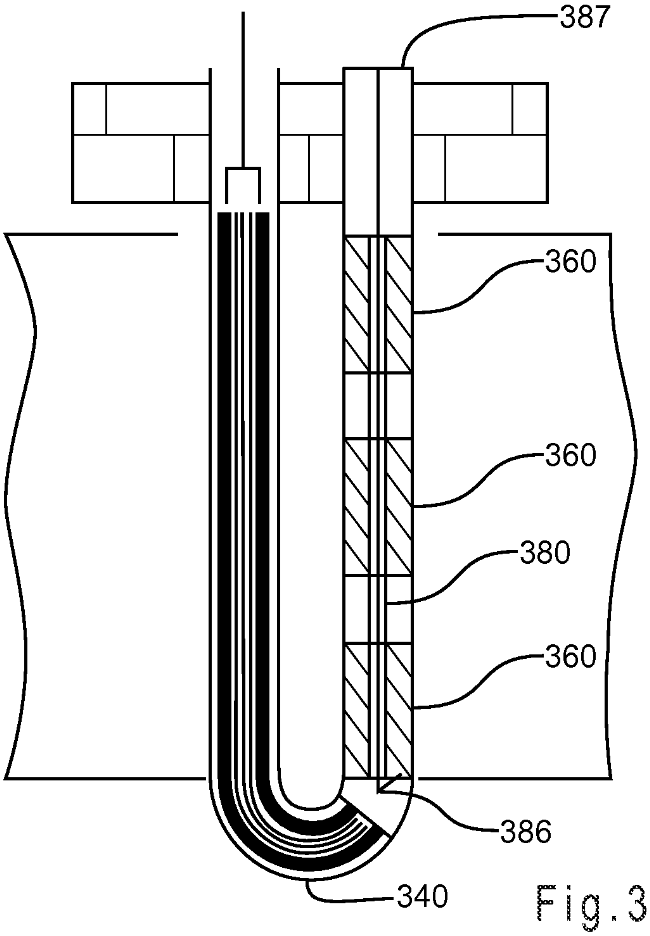

Fig.3D

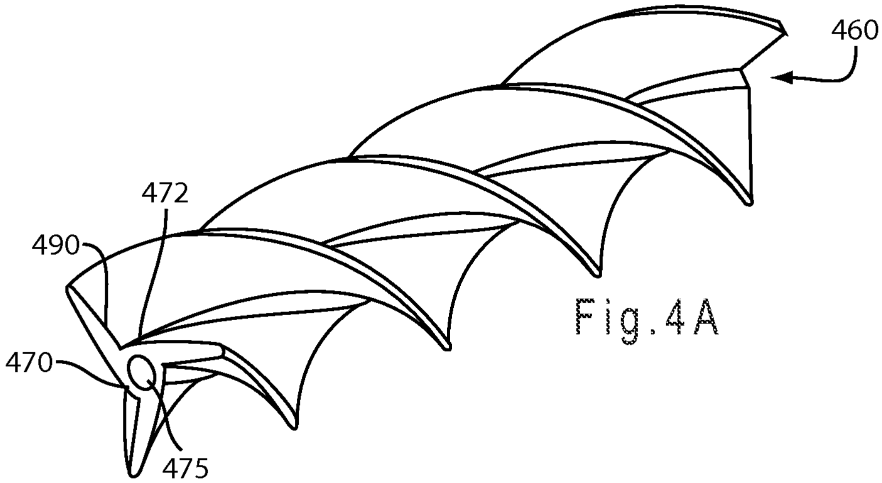

Fig.4A

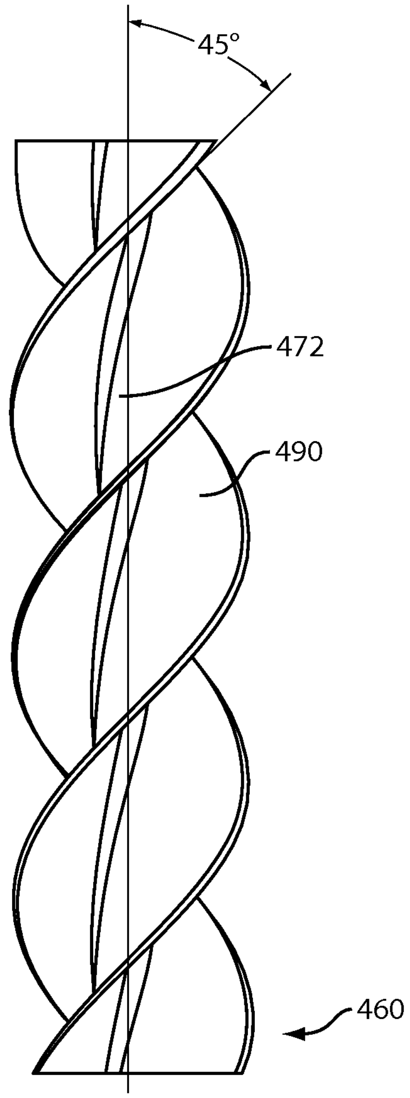

Fig.4B

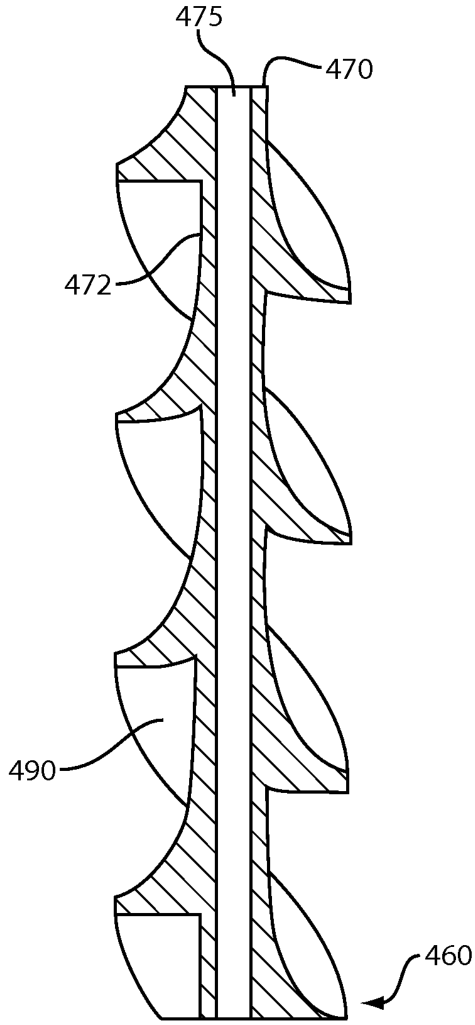

Fig.4C

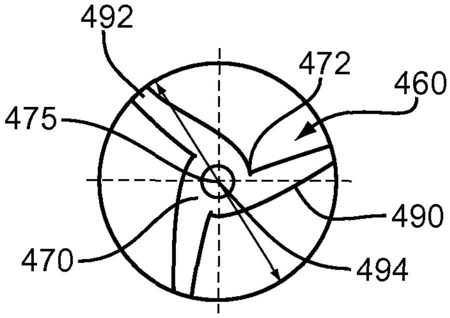

Fig.4D

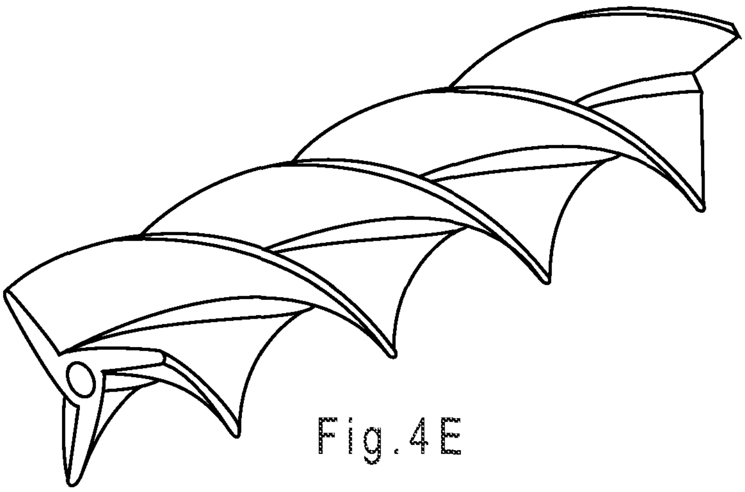

Fig.4E

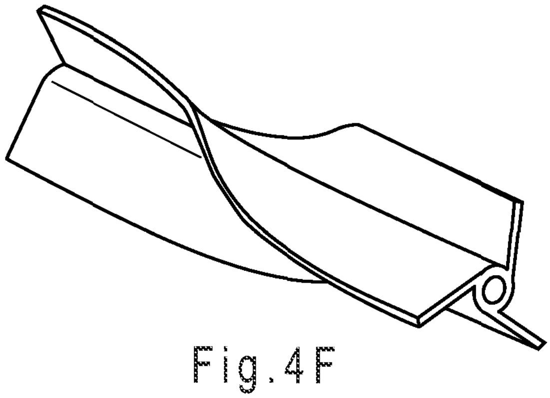

Fig.4F

$T_{amb} := (70 + 459) \cdot R$	Ambient Temperature
$T_H := (1800 + 459) \cdot R$	Temperature of Products of Combustion
$D_{RT} := 4 \cdot in$	Radiant Tube ID
$V'_{POC} := 1500 \cdot \frac{ft^3}{hr}$	Standard Volumetric Flow rate of Products of Combustion
$m'_{POC} := V'_{POC} \cdot \rho\left(T_{amb}\right)$ $m'_{POC} = 0.014 \frac{kg}{s}$	Mass Flow Rate of Products of Combustion
$V'_{HPOC} := \frac{m'_{POC}}{\rho\left(T_H\right)}$	Volumetric Flow rate of Hot Products of Combustion
$D_{RT} := 4 \cdot in$	Diameter of Radiant Tube
$V_{POC} := \frac{V'_{HPOC}}{\left(\frac{\pi}{4} \cdot D_{RT}^{\ 2}\right)}$ $V_{POC} = 6.23 \frac{m}{s}$	Velocity of Hot Products of Combustion
$RE_{POC} := \frac{V_{POC} \cdot D_{RT}}{\nu\left(T_H\right)}$	Reynolds number for flow inside a tube
$RE_{POC} = 3.742 \times 10^3$	Reynolds Number for flow of hot products of combustion inside a 4" diameter radiant tube < 2300 is laminar

Fig.4G-1

	Radiant Heating Element Analysis
$N := 3$	Number of wings
$R := \frac{D_{RT}}{2}$	Wing length
$P := R \cdot 2 + \pi \cdot \frac{D_{RT}}{N}$	Perimiter formed between wings
$A_c := \frac{\frac{\pi}{4} \cdot D_{RT}^{\ 2}}{N}$	Cross sectional area between wings
$D_h := \frac{4A_c}{P}$ $\quad D_h = 2.046\text{in}$	Hydraulic diameter formed between wings

Entrance Velocity remains the same

$$RE_{RHE} := \frac{V_{POC} \cdot D_h}{\nu(T_H)}$$

$$RE_{RHE} = 1.914 \times 10^3$$

Reynolds number for flow between two wings of a radiant heating element
< 2300 is laminar flow

$$L_h := .05 \cdot RE_{RHE} \cdot D_h$$

Fig.4G-2

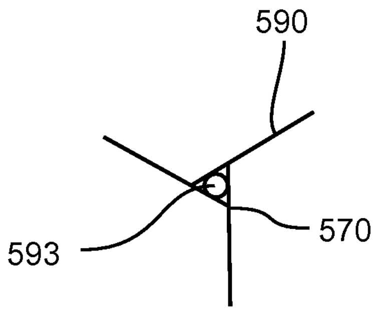

Fig.5A

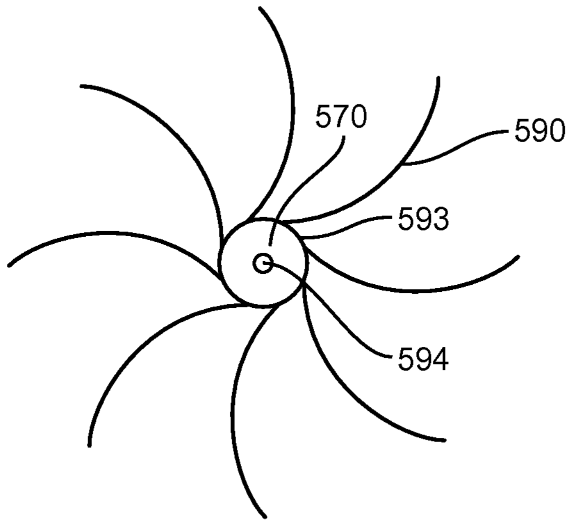

Fig.5B

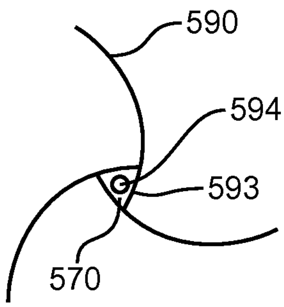

Fig.5C

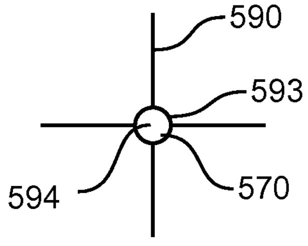

Fig.5D

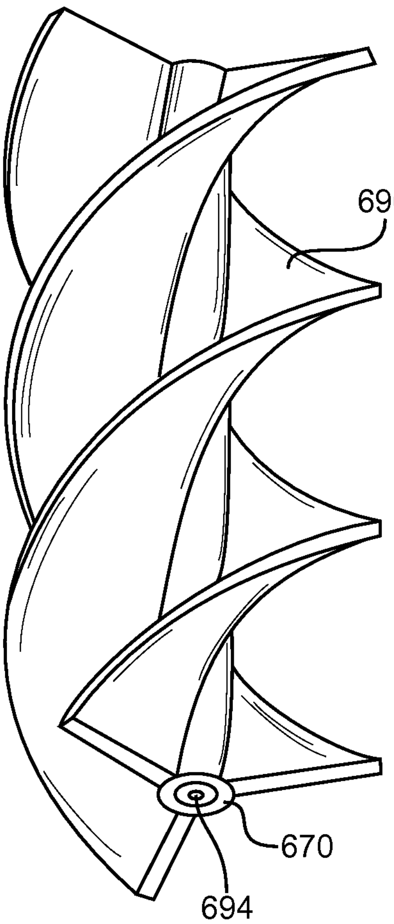

Fig.6A

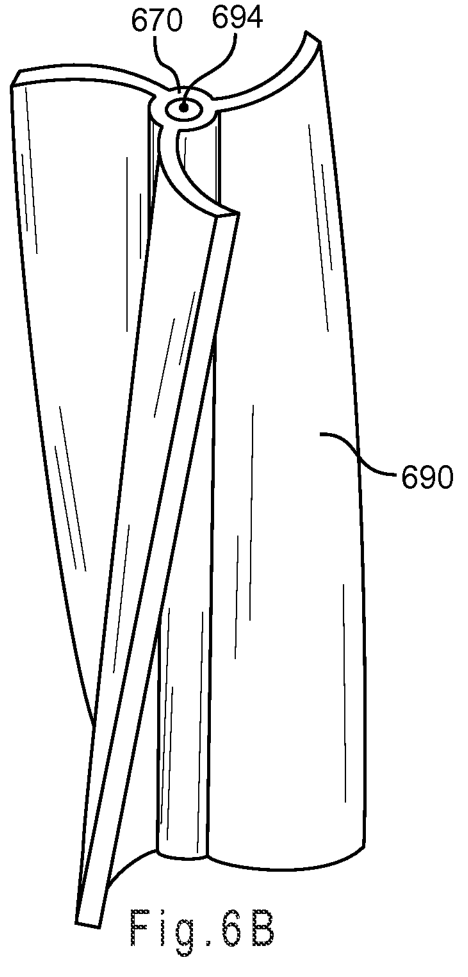

Fig.6B

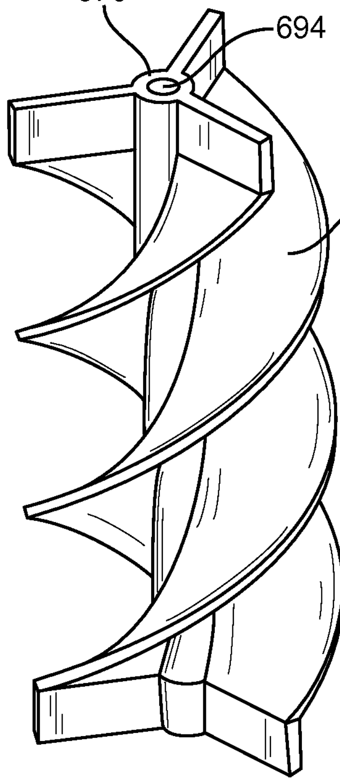

Fig.6C

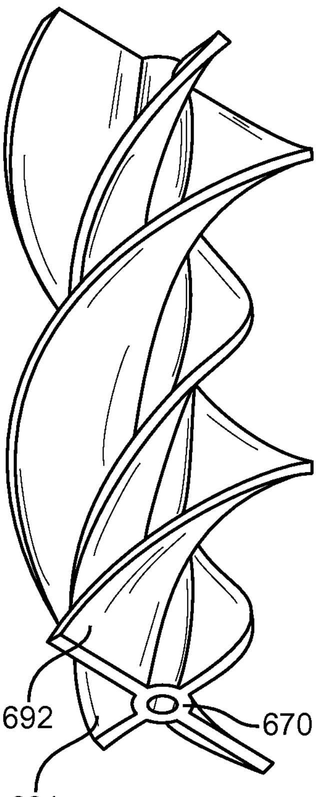

Fig.6D

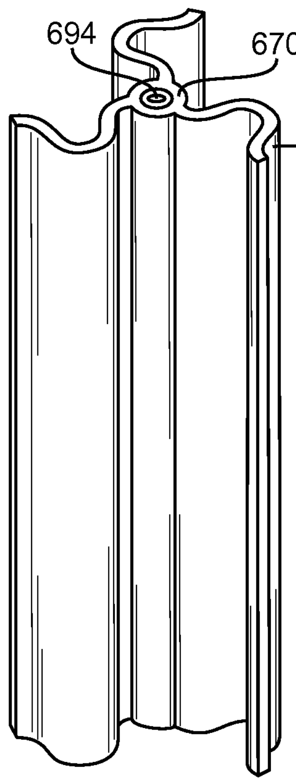

Fig.6E

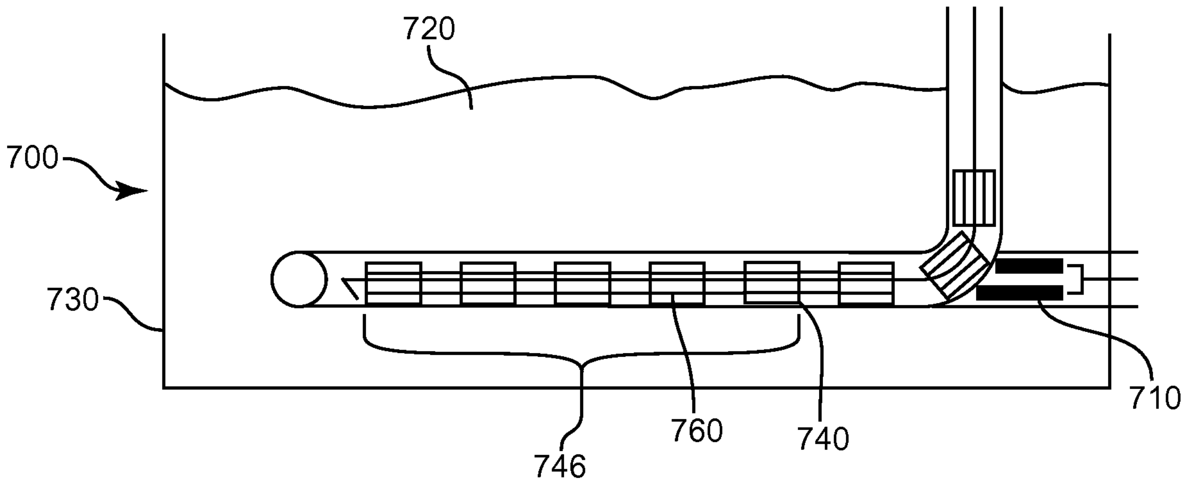

Fig.7

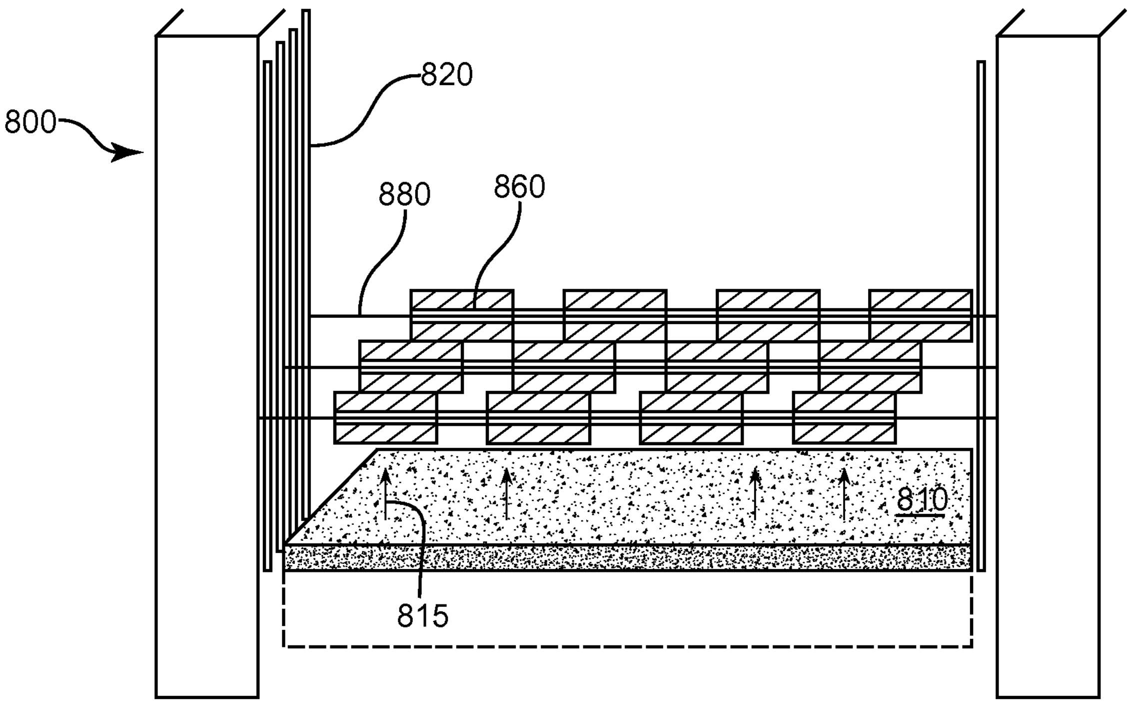

Fig.8

REFERENCES CITED IN THE DESCRIPTION

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