The invention is for an apparatus and method for removal of waste heat from heat-generating components including high-power solid-state analog electronics such as being developed for hybrid-electric vehicles, solid-state digital electronics, light-emitting diodes for solid-state lighting, semiconductor laser diodes, photovoltaic cells, anodes for x-ray tubes, and solids-state laser crystals. Liquid coolant is flowed in one or more closed channels having a substantially constant radius of curvature. Suitable coolants include electrically conductive liquids (including liquid metals) and ferrofluids. The former may be flowed by magneto-hydrodynamic effect or by electromagnetic induction. The latter may be flowed by magnetic forces. Alternatively, an arbitrary liquid coolant may be used and flowed by an impeller operated by electromagnetic induction or by magnetic forces. The coolant may be flowed at very high velocity to produce very high heat transfer rates and allow for heat removal at very high flux.
THERMAL INTERFACE DEVICE
CROSS-REFERENCE TO RELATED APPLICATIONS


FIELD OF THE INVENTION

[0002] This invention relates generally to a heat removal from heat-generating components and more specifically to a heat removal of heat at high flux.

BACKGROUND OF THE INVENTION


[0004] There are many devices that generate waste heat as a byproduct of their normal operations. These include analog solid-state electronic components, digital solid-state electronic components, semiconductor laser diodes, light emitting diodes for solid-state lighting, solid-state laser components, laser crystals, vacuum electronic components, and photovoltaic cells. Waste heat must be efficiently removed from such components to prevent overheating and consequent loss of efficiency, malfunction, or even catastrophic failure. Methods for waste heat management may include conductive heat transfer, convective heat transfer, and radiative heat transfer, or various combinations thereof. For example, waste heat removed from heat generating components may be transferred to a heat sink by a flowing heat transfer fluid. Such a heat transfer fluid is also known as a coolant.

[0005] Cooling requirements for the new generation of heat-generating components (HGC) are very challenging for thermal management technologies of prior art. For example, an ongoing miniaturization of semiconductor digital and analog electronic devices requires removal of heat at ever increasing fluxes that may be on the order of several hundreds of watts per square centimeter, or even higher. Traditional heat sinks and heat spreaders have a large thermal resistance, which may contribute to elevated junction temperatures and, may cause reduced HGC device reliability. As a result, removal of heat often becomes the limiting factor and a barrier to further performance enhancements for HGC. More specifically, a new generation of high-power semiconductor chips for electric current inverters used in hybrid electric vehicles and future plug-in hybrid electric vehicles requires improved thermal management to boost heat transfer rates, eliminate hot spots, and reduce volume, while allowing for operation at higher electric current density. See, for example, “High-Performance Heat Sink for Hybrid Electric Vehicle Inverters,” by J. Vetvrec, published by the American Society of Mechanical Engineers (ASME) as a Paper No. DETC2010-28776 in August 2010.

[0006] High-brightness light emitting diodes (LED) being developed for solid-state lighting for general illumination in commercial and household applications also require improved thermal management. These new light sources are becoming of increased importance as they offer up to 75% savings in electric power consumption over conventional lighting systems. Waste heat must be effectively removed from the LED chip to reduce junction temperature, thereby prolonging LED life and making LED cost effective over traditional lighting sources.

[0007] Another class of electronic components requiring improved cooling are semiconductor-based high-power laser diodes used for direct material processing and for pumping of solid-state lasers. Generation of optical output from laser diodes is accompanied by production of large amount of waste heat that must be removed at a flux on the order of several hundreds of watts per square centimeter. In addition, the temperature of high-power laser diodes must be controlled within a narrow range to avoid undesirable shifts in wavelength of the optical output. See, for example, “Progress in the Development of Active Heat Sink for High-Power Laser Diodes,” by J. Vetvrec, R. Feeler, and S. Bonham, published by The International Society for Optical Engineering (SPIE) as a paper number 7583-19 in January 2010.

[0008] Photovoltaic cells (solar electric cells and thermophotovoltaic cells) are becoming increasingly important for generation of electricity. Such cells may be used with concentrators to increase power generation per unit area of the cell and thus reduce initial installation cost. This approach requires removal of waste heat at increased flux. Similarly, high-performance crystals used in solid-state lasers generate waste heat that may require removal at fluxes in the neighborhood of thousand watts per square centimeter.

[0009] Anodes in x-ray tubes are subjected to very high thermal loading. Rotating anodes are frequently used to spread the heat to avoid overheating. Such rotating anodes inside a vacuum enclosure are impractical for use in a new generation of x-ray tubes for use in compact and portable devices in medical and security applications. A compact and lightweight heat transfer component having no moving parts inside the vacuum enclosure is very desirable.

[0010] Current approaches for removal of waste heat at high fluxes include 1) spreading of heat with elements having high thermal conductivity and/or 2) forced convection cooling using liquid coolants. However, even with heat spreading materials having extremely high thermal conductivity such as diamond films and certain graphite or graphene fibers, a significant thermal gradient is required to conduct large amount of heat even over short distances. In addition, passive heat spreaders are not conducive to temperature control of the HGC. Forced convection methods for removal of waste heat at high fluxes may use microchannel heat exchangers or impingement jets to obtain desirable heat transfer coefficient with conventional coolants such as water, alcohol, Freon, or ethylene glycol. Known forced convection systems have many components, are bulky, heavy, and have geometries that
require the coolant to make complex directional changes while traversing the coolant loop. Such directional changes are a potential source of increased flow turbulence causing higher pressure drop in the loop and, therefore, necessitate higher pumping power. In optical components such as laser crystals, coolant turbulence may result in deleterious fluid-induced vibrations causing misalignment of optical beams.

[0011] Metals have a thermal conductivity several orders-of-magnitude greater than water and organic liquids. Liquid (molten) metals have a viscosity comparable to that of water. As a result, liquid metals are excellent candidates for advantageous cooling in many demanding applications, especially where heat must be removed at high heat flux. Initially, liquid metal cooling may have been developed for thermal management of nuclear reactors on submarines in the 1950’s. These large systems have used eutectic alloy of sodium and potassium (also known as NaK) and in some cases, eutectic alloys of lead and bismuth. There may be a significant prior art in connection with these large-scale systems.

[0012] Liquid metal cooling for small commercial applications (e.g., electronics) is deemed to have been enabled by the discovery of a low melting point (reported as -19°C) eutectic alloy of gallium, indium, and tin (see, for example, U.S. Pat. No. 5,800,060), commercially known under the name “gallistan.” Gallistan is non-toxic, stable in air, and has excellent surface wetting properties. This opportunity was recognized in several recent disclosures, for example, U.S. Pat. Nos. 7,505,272, 7,697,291, 7,539,016, 7,764,499, 7,701, 716, 7,672,129, 7,245,495, 7,861,769, and 7,131,286. To date, no devices based on these disclosures are known to have appeared on the market.

[0013] The above disclosures typically suggest a traditional layout for a thermal management system: a heat exchanger (HEX) for receiving heat, HEX for rejecting heat, plumbing, and a pump for flowing the liquid metal. Such configurations may not self-contained and may be impractical for many applications because they may have a large size, may not sealed, may use incompatible materials, and may have large electromagnetic interference (EMI). In addition, above disclosures do not address the challenges of handling and pumping liquid metal, namely:

[0014] 1) Gallistan has a specific gravity of about 6.4, which means that gallistan flow loop may require nearly 7-times more pumping power to operate than a comparable water flow loop having the same flow velocity.

[0015] 2) Gallium alloys have a tendency to form amalgams with other metals, which may result in severe corrosion in commonly used engineering metals. In addition, the solid inter-metallic compounds produced by the corrosive action may form deposits inside the liquid metal flow channel, impeding the heat transfer, and possibly block the flow channels.

[0016] 3) Pumping of liquid metal with an electromagnetic pump may be very simple in theory, but it may be challenging in practice due to possible complex magneto-hydrodynamic (MHD) boundary layers and MHD instabilities.

[0017] 4) Specific heat of liquid metal per unit volume may be only about half of that of water. Hence, a liquid metal cooling loop may require higher flow velocities to carry away the same amount of heat as a comparable water loop with the same temperature rise. This means that, a liquid metal cooling loop operating at low velocity may not be much more effective (and may be actually less effective) than a comparable water loop.

[0018] The above indicates that for a performance superior to conventional cooling systems, a liquid metal cooling hardware may not have an arbitrary configuration and/or arbitrary operating parameters.

[0019] In summary, prior art does not teach a heat transfer device capable of removing heat at very high fluxes on the order of several hundreds of watts per square centimeter that is also compact, lightweight, self-contained, capable of accurate temperature control, has a low thermal resistance, and requires very little power to operate. It is against this backdrop that the significant improvements and advancements of the present invention have taken place.

SUMMARY OF THE INVENTION

[0020] The present invention provides a heat transfer device (HTD) for removal of waste heat from a heat generating component (HGC). The HTD of the present invention flows a liquid coolant in a closed and sealed channel having a substantially constant radius of curvature. The liquid coolant removes high-flux waste heat from the HGC and transfers it at a much reduced flux to a heat sink. For example, the HTD may transfer acquired heat to a structure, heat pipe, secondary liquid coolant, phase change material (PCM), gaseous coolant, or ambient air.

[0021] A unique design of the HTD flow channel in combination with an effective pumping mechanism make it possible to flow liquid coolant in the channel at high velocity with only modest amount of pumping power. Channel curvature under the heat load results in a centrifugal force, which provides a good coolant flow attachment to channel wall and boundary layer mixing. High flow velocity, good flow attachment, and good thermal conductivity of the liquid coolant offer effective removal of waste heat from the HGC at high flux and with a low thermal resistance. The HTD of the subject invention may be used to cool HGC such as, but not limited to, solid-state electronic chips, semiconductor laser diodes, light emitting diodes for solid-state lighting, solid-state laser components, laser crystals, optical components, vacuum electronic components, and photovoltaic cells.

[0022] In one preferred embodiment of the present invention, the HTD comprises a body having a first surface, a second surface, and a closed flow channel. The first surface is adapted for receiving heat from a heat generating component and the second surface is adapted for transferring heat to a heat sink. The flow channel has a substantially constant radius of curvature in the flow direction. An electrically conductive liquid coolant is flowed inside the flow channel by means of a magneto-hydrodynamic (MHD) effect (MHD drive).

[0023] In another preferred embodiment of the present invention, electrically conductive liquid or ferrofluid coolant may be used and flowed by the means of a moving magnetic field. Moving magnetic field induces eddy currents in the electrically conductive coolant that, in turn, provide force coupling to the coolant (inductive drive). Alternatively, moving magnetic field directly couples into the ferrofluid (magnetic drive). Suitable moving magnetic field may be generated by a rotating magnet.

[0024] In yet another preferred embodiment of the present invention, the moving (rotating or traveling magnetic) magnetic field may be generated by stationary electromagnets operated by alternate current in an appropriate poly-phase relationship. In a still another embodiment of the present
invention, the coolant is an arbitrary liquid flowed in a closed channel with a substantially constant radius of curvature. The coolant flow is induced by a rotating impeller (impeller drive) spun by mechanical means, rotating magnetic field, moving magnetic field, or by electromagnetic induction. In a variant of the invention the coolant may be directed into impinge onto the flow channel wall opposite to the HGC to further improve the rates for removal of waste heat from the HGC.

Accordingly, it is an object of the present invention to provide a heat transfer device (HTD) for removing waste heat from HGC. The HTD of the present invention is simple, compact, lightweight, self-contained, can be made of materials with a coefficient of thermal expansion (CTE) matched to that of the HGC, requires relatively little power to operate, and is suitable for large volume production.

It is another object of the invention to provide means for cooling HGC.

It is still another object of the invention to provide means for temperature control of HGC.

It is yet another object of the invention to cool a semiconductor electronic components.

It is yet further object of the invention to cool semiconductor laser diodes.

It is a further object of the invention to cool LED for solid-state lighting.

It is still further object of the invention to cool computer chips.

It is an additional object of the invention to cool photovoltaic cells.

It is still additional object of the invention to cool electronic chips in inverters for inverting direct-current from a battery to a three-phase alternating current for a traction motor in hybrid electric vehicles and electric vehicles.

These and other objects of the present invention will become apparent upon a reading of the following specification and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a side cross-sectional view of a heat transfer device (HTD) in accordance with one embodiment of the subject invention using a magneto-hydrodynamic (MHD) drive.

FIG. 1B is a cross-sectional view 1B-1B of the HTD of FIG. 1A.

FIG. 2A is an enlarged view of portion 2A of the HTD of FIG. 1A.

FIG. 2B is an enlarged view of portion 2B of the HTD of FIG. 1B.

FIG. 3 is an enlarged view of an alternative portion 2B of the HTD of FIG. 1B showing a flow channels with surface extensions.

FIG. 4 is an enlarged view of another alternative portion 2B of the HTD of FIG. 1B showing multiple flow channels arranged side-by-side.

FIG. 5 is an enlarged view of portion 2A of the HTD of FIG. 1A showing an attachment of a laser diode array HGC.

FIG. 6 is an enlarged view of portion 2A of the HTD of FIG. 1A showing an attachment of a laser diode bar HGC.

FIG. 7 is an enlarged view of portion 2A of the HTD of FIG. 1A showing an attachment of a light emitting diode HGC.

FIG. 8 is an enlarged view of portion 9A of the HTD of FIG. 1A showing an attachment of a solid-state laser crystal HGC.

FIG. 9A is an enlarged view of portion 9A of the HTD of FIG. 1A showing details of the MHD drive.

FIG. 9B is an enlarged view of portion 9B of the HTD of FIG. 1B showing details of the MHD drive.

FIG. 9C is an isometric view of the MHD drive of FIG. 1A.

FIG. 10 shows an alternative HTD body having internal passages for flowing a secondary coolant.

FIG. 11A shows a variant of the alternative HTD having an internal passage for flowing a secondary coolant and alternative arrangement of components of the MHD drive.

FIG. 11B is cross-sectional view 11B-11B of the HTD of FIG. 11A showing details of the passage for flowing a secondary coolant.

FIG. 12 shows another alternative HTD body having external fins for heat transfer to gaseous coolant or ambient air.

FIG. 13A is a side cross-sectional view of an HTD in accordance with another embodiment of the subject invention wherein coolant flow is induced by a rotating magnetic field produced by a rotating magnet.

FIG. 13B is a cross-sectional view 13B-13B of the HTD of FIG. 13A.

FIG. 14A is a side cross-sectional view of an HTD in accordance with a yet another embodiment of the subject invention wherein coolant flow is induced by a rotating magnetic field produced by stationary electromagnets.

FIG. 14B is a cross-sectional view 14B-14B of the HTD of FIG. 14A.

FIG. 14C is a side cross-sectional view of a 3-phase electromagnet for use with the HTD of FIG. 14A.

FIG. 15 is a side cross-sectional view of an alternative HTD having externally mounted stationary electromagnets.

FIG. 16 shows a suitable connection of electromagnets to a single phase alternating current supply.

FIG. 17 shows a variant to the HTD in accordance with a yet another embodiment of the subject invention wherein the electromagnets are arranged to generate a translating electromagnetic field.

FIG. 18A is a side cross-sectional view of an HTD in accordance with still another embodiment of the subject invention using an impeller.

FIG. 18B is a cross-sectional view 18B-18B of the HTD of FIG. 18A.

FIG. 19 is a side cross-sectional view of an HTD in accordance with a further embodiment of the subject invention suitable for cooling by impingement flow.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Selected embodiments of the present invention will now be explained with reference to drawings. In the drawings, identical components are provided with identical reference symbols in one or more of the figures. It will be apparent to those skilled in the art from this disclosure that the following descriptions of the embodiments of the present invention are merely exemplary in nature and are in no way intended to limit the invention, its application, or uses.
Referring now to FIGS. 1A and 1B, there is shown a heat transfer device (HTD) 100 in accordance with one preferred embodiment of the subject invention. HTD 100 may generally comprise a body 102 and a magneto-hydrodynamic (MHD) pump 105. The body 102 may further comprise a first surface 106 adapted for receiving heat from a heat generating component (HGC), a second surface 108 adapted for rejecting heat to a heat sink, and a flow channel 104. The body 102 may be preferably made of a material having high thermal conductivity. Preferably, such a material may also have a relatively low electrical conductivity or such a material may be dielectric. Suitable materials for construction of the body 102 may include silicon (Si), beryllia (BeO), silicon carbide (SiC), and aluminum nitride (AIN). A heat generating component (HGC) 114 may be also attached to the first surface 106 and arranged to be in a good thermal communication therewith. HGC 114 may be, but it is not limited to a solid-state electronic chip, semiconductor laser diode, light emitting diodes (LED), solid-state laser crystal, optical component, x-ray tube anode, or a photovoltaic cell. If desired, the body 102 may be made from material having a coefficient of thermal expansion (CTE) matched to the CTE of the HGC 114. In some variants of the subject invention the body 102 can be a composite unit made of several suitably joined different materials. For example, portions of the body 102 in proximity of the HGC 114 may be made of material having high thermal conductivity to facilitate efficient conduction of heat. While portions of the body 102 in proximity of the MHD pump 105 may be made of material having poor electrical conductivity to prevent electrical shorting.

The second surface 108 is arranged to be in a good thermal communication with a heat sink (not shown). Suitable heat sinks include a structure, heat pipe, secondary liquid coolant, phase change material (PCM), gaseous coolant, or ambient air. When a fluid used as a heat sink, it may employ natural convection or forced convection to remove heat from the second surface 108. The second surface 108 may also include surface extensions such as fins or ribs to enhance heat transfer therewith.

Referring now to FIGS. 2A and 2B, the HGC 114 may be thermally coupled to the first surface 106 with a suitable joining material 120. Preferably, joining material 120 has a good thermal conductivity. Suitable joining materials include solder, thermally conductive paste, epoxy, liquid metals, and adhesives. Alternatively, HGC 114 may be diffusion bonded onto surface 106. As another alternative, the HGC 114 may be mechanically attached onto surface 106. The flow channel 104 comprises an outer surface 110 and an inner surface 112. Each of the surfaces 110 and 112 may have a width “W” and they may be separated from each other by a distance “D”. Preferably, the surface 110 has a constant radius of curvature “R” and the inner surface 112 has a radius “R’ minus “H” (“R’+H”). For example, surfaces 110 and 112 may each be cylindrical and mutually concentric, thereby giving the flow channel 104 a general shape of a hollow cylinder with an outer radius “R”, and an inner radius “R’+H”, and height “W”. More generally, the flow channel may have a shape of a toroid, which is a geometrical object generated by revolving a geometrical figure around an axis external to that figure. For example, the geometrical figure revolved may be a polygon. In particular, the geometrical figure may be a rectangle having a width “W” and height “H”. Because the channel forms a closed loop, it may be also referred to in this disclosure as the “closed flow channel.” Preferred range for the width “W” is 0.1 to 20 millimeters, but dimensions outside this range may be also practiced. Preferred range for the outer radius of curvature “R” is 5 to 25 millimeters, but dimensions outside this range may be also practiced. Preferably, the distance “H” is chosen so that the wall 104 has a hydraulic diameter (2WH(W+H)) about five (5) micrometers to three (3) millimeters, and most preferably about ten (10) micrometers to one (1) millimeter. In addition, surfaces 110 and 112 should be made very smooth. Preferably, surfaces 110 and 112 are finished to surface roughness of less than 8 micrometers root-mean-square value, and most preferably to surface roughness of less than 1 micrometer root-mean-square value. Surfaces of the flow channel 104 may also have a coating to protect them from corrosion. The first surface 106 may be generally tangential to the outer surface 110 and separated from it by a distance “S” (FIG. 2B). Preferred range for the distance “S” is 0.1 to 1 millimeter, but dimensions outside this range may be also practiced.

The flow channel 104 contains a suitable electrically conductive liquid coolant 116. Preferably, the liquid coolant 116 has a good thermal conductivity, low viscosity, and low freezing point. Suitable liquid coolants 116 include selected liquid metals. For the purposes of this disclosure, the term “liquid metal” shall mean suitable metals (and their suitable alloys) that are in a liquid (molted) state at their operating temperature. Liquid metals have a comparatively good thermal conductivity while being also electrically conductive and, in some cases have a relatively low viscosity. Examples of suitable liquid metals include mercury, gallium, indium, bismuth, tin, lead, potassium, and sodium. Ordinary or eutectic liquid metal alloys may be used. Examples of suitable liquid eutectic metal alloys include Indalloy 51 and Indalloy 60 (manufactured by Indium Corporation in Utica, N.Y.), gallinast (obtainable from Geratherm Medical AG in Geschwend, Germany). Gallinast is a nontoxic eutectic alloy of 68.5% by weight of gallium, 21.5% by weight of indium and 10% by weight of tin, having a melting point around minus 19 degrees Centigrade. Examples of suitable liquid metal alloys may be also found in the U.S. Pat. No. 5,800,060 issued to G. Speckbroke et al., on Sep. 1, 1998. If gallium-based liquid metal is used as a coolant 116, it is important that the surfaces of the flow channel 104 are made of compatible material. In particular, it is well known that liquid gallium and its alloys severely corrode many metals. Prior art indicates that certain refractory metals such as tantalum and tungsten may be stable in gallium. See, for example, “Effects of Gallium on Materials at Elevated Temperatures,” by W. D. Wilkinson, Argonne National Laboratory Report ANL-5027 (August 1953). To protect against corrosion, surfaces of the flow channel 104 may be coated with suitable protective film. Prior art indicates that TiN and certain organic coatings may be stable in gallium. In particular, TiN and diamond-like coating (DLC) may provide suitable protection to metals such as aluminum and copper from corrosion by gallium. Diamond-like coating may be obtained from Richter Precision in East Petersburg, Pa.

If such a protective coating on the wall of channel 104 is additionally dielectric, then the body 102 may be constructed from an electrically conductive material. If the body 102 is made of electrically conductive material and electrical insulation between HGC 114 and the body 102 is required, a thin (for example, 100-micron thick) wafer (not shown) of suitable electrically insulating material (for example, AlN) may be placed between the HGC 114 and the surface 106.
Preferably, the flow channel 104 is not entirely filled with the liquid coolant and at least some void space free of liquid coolant is provided inside the channel to allow for thermal expansion of the coolant. In particular, certain suitable coolant for use with the HTD 100 may undergo significant expansion upon freezing (solidification). The void space may prevent buildup of excessive pressure inside the channel 104 upon phase change of the coolant 116. The void space may be filled with air, gas, vapor, or it may contain a suitable elastic or crushable material (for example, polystyrene).

The outer surface 110 may also include extensions 118 to increase the contact area between the surface 110 and liquid coolant 116 (FIG. 3). Suitable form of surface extension 118 includes fins and ribs. Alternatively, multiple flow channels 104a-104c may be employed (FIG. 4). In some variants of the subject invention, a portion of the HGCl 114 may form a portion of the outer surface 110 of the flow channel 104. In such variants of the invention, the liquid coolant 116 may directly wet a portion of the surface of the HGCl 114. FIG. 5 shows a mounting of HGCl 114, which is an array of semiconductor laser diodes (or laser diode bars) 150 imbedded in a substrate 148 and producing optical output 152. Suitable array of semiconductor laser diode bars imbedded in a substrate known as “silver bullet laser diode assembly submodule” and as “golden bullet laser diode assembly submodule” may be obtained from Northrop-Grumman Cutting Edge Optronics in St. Charles, Mo. FIG. 6 shows a mounting of HGCl 114, which is a laser diode bar producing optical output 152. Suitable laser diode bar known as “unmounted laser diode bar” may be obtained from Northrop-Grumman Cutting Edge Optronics in St. Charles, Mo. FIG. 7 shows a mounting of HGCl 114”, which is a high-power light emitting diode producing optical output 153. Suitable high-power light emitting diode known as “Luxeon® K2” may be obtained from Philips Lumileds Lighting Company, Sun Valley, Calif. FIG. 8 shows a mounting of HGCl 114”, which is a solid-state laser crystal receiving optical pump radiation 151 and amplifying a laser beam 155. Suitable solid-state laser crystal may be in the form of a thin disk laser as, for example, described by Kafta et al., in the U.S. Pat. No. 7,003,011.

Referred now to FIGS. 9A, 9B and 9C, there is shown the MHD pump 105 comprising magnets 129a and 129b, yoke 131, electrodes 130a and 130b, and electrical conductors 126a and 126b. The magnets 129a and 129b may be arranged to generate magnetic field that traverses the flow channel 104 in a substantially radial direction in the proximity of electrodes 130a and 130b. Double arrow line 160 indicates preferred directions of the magnetic field. The double arrow 160 represents that the magnetic field may be substantially in one of the two directions indicated by the arrow heads. Magnets 129a and 129b are preferably permanent magnets, and most preferably rare earth permanent magnets. In particular, the magnets 129a and 129b may be substantially formed from samarium-cobalt or from neodymium-iron-boron material. Alternatively, the magnets 129a and 129b may be formed as electromagnets. The yoke 131 may be made from a suitable soft ferromagnetic material. Preferably, the yoke 131 is made of soft ferromagnetic material having high magnetic saturation, such as, but not limited to, iron, low carbon steel, vanadium supermendur, or Hiperco®.

The electrodes 130a and 130b are in electrical contact with the liquid coolant 116 and are arranged so that electric current may be passed through the coolant 116 in the region between the magnets 129a and 129b, and in a direction generally orthogonal to magnetic field direction. Preferably, the electrodes 130a and 130b are made of material having good electrical conductivity while being also substantially resistant to corrosion by gallium. For example, the electrodes 130a may be made of, but not limited to molybdenum, tungsten, niobium, or tantalum. Alternatively, the electrodes may be made of copper or copper alloy and they may be plated for improved corrosion resistance with a suitable refractory metal such as, but not limited to molybdenum, tungsten, niobium, tantalum, rhenium, osmium, and iridium. The electrodes 130a and 130b may be connected to external source of direct electric current via electric conductors 126a and 126b respectively. An electrically insulating feed-through 107 installed in the wall of yoke 131 may be provided to electrically insulate the conductors 126a and 126b from the yoke 131. The HTD 100 may further include a magnetic shield (not shown) to prevent adverse effect of magnetic field generated by magnets 129a and 129b on HGCl 114 and/or nearby components.

In operation, electric current is passed through the liquid coolant 116 between electrodes 130a and 130b. Because at least a portion of the coolant 116 is immersed in magnetic field having a vector component orthogonal to the electric current flowing though the coolant 116, a magneto-hydraulic (MHD) effect causes the coolant 116 to flow inside the channel 104. By appropriately choosing the direction of magnetic field and the direction of the current drawn through the coolant 116 between the electrodes 130a and 130b, the coolant 116 may be made to flow in the direction indicated by the arrows 124 in FIGS. 1A and 2A. As a result, the flow of coolant 116 may form a closed flow loop. Because the closed flow loop has a substantially constant radius of curvature and the walls of the flow channel 104 are smooth, the flow of coolant 116 encounters relatively little resistance. Hence, very high flow velocities of coolant 116 can be sustained with a relatively small amount of motive power. The curvature of channel 104 under the HGCl 114 beneficially results in a centrifugal force, which provides a good attachment of flow of coolant 116 to channel wall surface 110 and boundary layer mixing. High flow velocity, good flow attachment, and good thermal conductivity of the liquid coolant offer effective removal of waste heat from the HGCl 114 at high flux. This disclosure may also refer to the means for flowing the coolant by MHD effect as an “MHD drive.”

The HGCl 114 is operated and its waste heat is allowed to transfer through the first surface 106 into the body 102 and conducted to the outer surface 110 of the flow channel 104. The second surface 108 is maintained at a temperature substantially below the temperature of the HGCl 114. Liquid coolant 116 flowing at high velocity enables a very high heat transfer coefficient on the surface 110. Heat is transferred from the surface 110 into the liquid coolant 116, transported by the coolant 116, and deposited into other parts of the body 102. Heat deposited into other parts of the body 102 is conducted to the second surface 108 and transported therefrom to a suitable heat sink. Using the above process, HTD 100 removes heat from the HGCl 114 and transfers it to a heat sink or environment. For intermittently operating HGCl 114, the operation of the HTD 100 may be coordinated with the HGCl. For example, the HTD may be operated only when the HGCl generates a significant amount of waste heat.

FIG. 10 shows an HTD 100' having a body 102' with a second surface 108' formed as one or more internal passages 167' for flowing secondary liquid or gaseous coolant 185. The
secondary coolant 185 may be flowed in a direction generally transverse to the flow direction of the coolant 116 inside the flow channel 104. The MHD pump 105 (FIG. 1A) has been omitted in the view for clarity. FIGS. 11A and 11B shows an HTD 100' having a body 102' with a second surface 108' formed as an internal passage 167' for flowing a secondary liquid or gaseous coolant 185. The MHD pump 105 (FIG. 1A) has been omitted in the view for clarity. The passage 167' may be formed between a jacket 189 and the body 102' in proximity of the flow channel 104. The jacket 189 is preferably formed from a soft ferromagnetic material to provide a magnetic flux return for the magnet 129. The magnet 129 may be formed as a generally cylindrical body and provided with a magnetization in a generally diametral direction indicated by the double arrow 160. Preferably, the secondary coolant 185 is flowed in the direction (as indicated by arrows 179) generally opposite to the direction of the coolant 116 flowing inside the flow channel 104 (as indicated by arrows 124). FIG. 12 shows an HTD 100' having a body 102' with a second surface 108' formed as external fins 154 for transferring heat to a liquid coolant, gaseous coolant, or ambient air. The MHD pump 105 (FIG. 1A) has been omitted in the view for clarity.

[0076] The temperature of the HGC 114 may be controlled by controlling the flow velocity of the coolant 116. The latter can be accomplished by controlling the current drawn through the coolant 116 via electrodes 130a and 130b. For example, by drawing more current through the coolant 116, the coolant flow velocity may be increased, and the HGC waste heat may be removed at a lower temperature differential between the HGC and the heat sink. Conversely, by drawing less current through the coolant 116, the coolant velocity may be decreased, and the HGC waste heat may be removed at a higher temperature differential between the HGC and the heat sink. Thus, by drawing more current through the coolant 116, the temperature of the HGC 114 may be decreased, and by drawing less current through the coolant 116, the temperature of the HGC 114 may be increased. An automatic closed-loop temperature control of the HGC 114 can be realized by sensing HGC temperature (for example, with a thermocouple) and using this information to appropriately control the current drawn through the coolant 116. In particular, if the HGC 114 is an LED, its temperature may be inferred from the output light spectrum. A means for sensing the LED light spectrum may be provided for this purpose. If the HGC 114 is a semiconductor laser diode, its temperature may be inferred from the output light center wavelength. A means for sensing the semiconductor laser diode output light center wavelength may be provided for this purpose. If the HGC 114 has electric currents flowing therethrough, HGC temperature may be determined from certain current and/or voltages supplied to or flowing through in the HGC. If the coolant used in the HTD 100 is susceptible to freezing (solidifying) due to ambient conditions during inactivity, the HTD may be equipped with an electric heater to warm the coolant up to at least its melting point. HGC 114 may also be relocated to warm up the HTD.

[0077] Referring now to FIGS. 13A and 13B, there is shown a heat transfer device (HTD) 200 in accordance with another preferred embodiment of the subject invention. HTD 200 is similar to HTD 100, except that in HTD 200 the coolant 216 inside the flow channel 204 may be an electrically conductive liquid or a ferrofluid. In addition, the MHD pump 105 (FIG. 1A) is not used. Instead, the flow of the coolant 216 may be caused by a rotating magnetic field. The flow channel 204 in HTD 200 may be of the same construction as the flow channel 104 in HTD 100. Ferrofluids are composed of nanoscale ferromagnetic particles suspended in a carrier fluid, which may be water, an organic liquid, or other suitable liquid. Certain water-based ferrofluids such as W11 available from FerroTec in Bedford, N.H., are also electrically conductive. Ferrofluids using a liquid metal or liquid metal alloy as a carrier fluid have been reported in prior art; see, for example, an article by J. Popplewell and S. Charles in New Sci. 1980, 97(1220), 332. The nano-particles are usually magnetite, hematite or some other compound containing iron, and are typically on the order of about 10 nanometers in size. This is small enough for thermal agitation to disperse them evenly within a carrier fluid, and for them to contribute to the overall magnetic response of the fluid. The ferromagnetic nano-particles are coated with a surfactant to prevent their agglomeration (due to van der Waals and magnetic forces). Ferrofluids may display paramagnetism, and are often referred to as being “superparamagnetic” due to their large magnetic susceptibility. It should be noted that ferrofluid may become magnetically saturated at a rather low magnetic fields of less than 0.1 Tesla (1.000 gauss). Alternatively, liquid coolant 216 may comprise a liquid having significant paramagnetic, diamagnetic, or ferromagnetic properties.

[0078] The body 202 is similar to body 102 of HTD 100 (FIG. 1A) except that it has a round central opening 264. The body 202 further comprises a first surface 206 adapted for receiving heat from HGC 114, a second surface 208 adapted for transferring heat to a suitable heat sink. Furthermore, the body 202 may be also constructed from a variety of materials preferably having high thermal conductivity. For example, the body 202 may be constructed from copper, copper-tungsten alloy, aluminum, molybdenum, silicon, and silicon carbide. The body 202 may also be constructed in part or in whole from ferromagnetic materials to provide return for magnetic flux lines and/or to shield adjacent components from magnetic field. Depending on the choice of coolant 216, the surfaces of the flow channel 204 may require appropriate protective coating to prevent corrosion. HTD 200 further comprises a magnet 234 rotatably suspended inside the opening 264 and positioned so that a significant portion of magnetic field lines cross the flow channel 204. The label “N” designates the north pole of the magnet and the label “S” designates the south pole of the magnet 234. The magnet 234 and the ferromagnetic material in the body 202 (if used) are preferably arranged so that when the magnet 234 is rotated, a given portion of the coolant 216 is alternatively exposed to large variations in magnetic field level, and most preferably to a magnetic field with alternating direction. When the coolant 216 is a ferrofluid, the variations in magnetic field amplitude should include magnetic field level substantially lower than the saturation magnetic field of the ferrofluid. In addition, the peak magnetic field preferably may be comparable to the saturation field of the ferrofluid. Certain ferrofluids may saturate at about 600 Gauss (0.06 Tesla). Preferably, the magnetic field within said coolant may include magnetic field values of less than 50 Gauss (0.005 Tesla). Typical range of speeds for rotating the magnet 234 may be from 600 revolutions per minute to 10,000 revolutions per minute.

[0079] Operation of HTD 200 is similar to the operation of HTD 100 except that the flow of the coolant 216 is caused by different means than flow of the coolant 116 in HTD 100. In particular, magnet 234 is rotated in the direction of arrow 238 to generate a rotating magnetic field. The magnet 234 may be rotated mechanically by a shaft 236 that may be coupled to an
external drive such as an electric motor. For example, if the surface 208 is cooled by air (see, e.g., FIG. 12) supplied by a fan driven by an electric motor, the magnet 234 may be attached to the output shaft of that motor. Alternatively, the magnet 234 may be rotated by means of a magnetic coupling to an external rotating magnetic component. As another alternative, the magnet 234 may be rotated by a rotating magnetic field generated by electromagnets. As a yet another alternative, the magnet 234 may be rotated by a turbine operated by a secondary coolant flowing through the central opening 264.

If the coolant 216 is an electrically conductive liquid, time varying magnetic field produced by the rotation of the magnet 234 induces eddy currents in the electrically conductive coolant 216. Such eddy currents, interact with the rotating magnetic field produced by the magnet 234 thereby establishing a force coupling between the rotating magnet 234 and the coolant 216. As a result, rotating magnet 234 exerts a force onto the coolant 216 causing the coolant 216 to flow inside the flow channel 204 in the direction of the arrow 222 thereby forming a flow loop. This disclosure may refer to the means for flowing an electrically conductive coolant by rotating magnetic field as an "inductive drive." Additional information about eddy current devices may be found in "Permanent Magnets in Theory and Practice," chapter 7.6: Eddy-Current Devices, by Malcolm McCraig, published by Pentech Press, Plymouth, UK, 1977; and in "An Introduction to Magneto-hydrodynamics," chapter 5, section 5.5: Rotating Fields and Swirling Motions, by P.A. Davidson, published by Cambridge Texts in Applied Mathematics, Cambridge University Press, Cambridge, UK, 2001.

If the coolant 216 is a ferrofluid, magnetic field produced by the rotating magnet 234 directly couples into the coolant 216 and flows it inside the flow channel 204 in the direction of the arrow 222. Rotational speed of the magnet 234 may used to control the flow velocity of the coolant 216. Thus, controlling the rotational speed of the magnet 234 allows to control the rate of heat removal from the HGC 114 and, thereby to control the HGC temperature. This disclosure may refer to the means for flowing ferrofluid coolant by rotating magnetic field as "magnetic drive."

Referring now to FIGS. 14A and 14B, there is shown a heat transfer device (HTD) 300 in accordance with yet another preferred embodiment of the subject invention. HTD 300 is essentially the same as HTD 200, except that in HTD 300 the rotating magnetic field for flowing the liquid coolant 316 is generated by stationary electromagnet coils 332a, 332b, and 332c, rather than a rotating magnet 234. The coils 332a, 332b, and 332c are preferably installed inside the central opening 364 as shown in FIG. 14A, and supplied with poly-phase alternating electric currents. Phases of the alternating currents supplied to the coils 332a, 332b, and 332c are set so that the combined magnetic field produced by the coils has a rotating component. For example, the electromagnet coils 332a, 332b, and 332c may be connected in a delta or star (Y) configuration as is often practiced in the art of three-phase alternating current systems (see, for example, "Standard Handbook for Electrical Engineers," D. G. Fink, editor-in-chief, Section 2: Electric and Magnetic Systems, Three-Phase Systems, Tenth Edition, published by McGraw-Hill Book Company, New York, N.Y., 1968) and supplied with an ordinary three-phase alternating current. Rotating magnetic field couples into the coolant in an already described manner and causes the coolant 316 to flow around the closed loop.

One skilled in the art can appreciate that there is a variety of electromagnet coil configurations fed by poly-phase alternating currents that can produce a time varying magnetic field with a rotating component (see, for example, "Magnetoelectric Devices, Transducers, Transformers, and Machines," by Gordon D. Slemon, Chapter 5: Polyphase Machines, published by John Willey & Sons, New York, N.Y., 1966). Electromagnet coils 332a, 332b, and 332c may be placed on a ferromagnetic core 383 such as shown in FIG. 14C.

FIG. 15 shows a heat transfer device (HTD) 300 which is variant of the HTD 300. The HTD 300 has electromagnet coils 332a, 332b, and 332c mounted on a flux return 333 located outside the HTD body 302. The flux return 333 is preferably made of suitable soft ferromagnetic material. The body 302 is preferably made from non-magnetic material except for the core portion 303, which is preferably made from a suitable soft ferromagnetic material. Suitable soft ferromagnetic material may include iron, silicon steel, or vanadium permendur. Preferably, suitable soft ferromagnetic material may be provided in form of transformer plates.

If only a single phase current is available, electromagnet coils 332a, 332b, and 332c may be combined with a capacitor 356 as shown, for example, in FIG. 16 to produce a suitable rotating magnetic field. There is a variety of similar connections practiced in the art of single phase electric motors. Frequency of the alternating currents supplied to the electromagnet coils 332a, 332b, and 332c may be used to control the flow velocity of the coolant 216. Thus, controlling the frequency of the alternating currents allows to control the rate for heat removal from the HGC 114 and the HGC temperature. Typical range for alternating current frequency is from 10 to 1000 cycles per second. Alternatively, the coolant flow velocity may be controlled by controlling the electric current supplied to the electromagnets.

FIG. 17 shows an HTD 300' that is a variant to the HTD 300 wherein the electromagnet coils 332a, 332b, and 332c are arranged to generate a traveling magnetic field rather than a rotating magnetic field. In particular, the electromagnet coils 332a, 332b, and 332c are arranged as often practiced in the art of linear electric motors and supplied with poly-phase alternating current in appropriate phase relationship. The resulting magnetic field is traveling generally in a linear path and it couples into the electrically conductive or ferrofluid coolant in the manner already described in connection with the HTD 300. It can be appreciated by those skilled in the art that the traveling magnetic field may cause the coolant 316 to flow even if the flow channel 304 may not have a substantially constant radius of curvature.

Referring now to FIGS. 18A and 18B, there is shown a heat transfer device (HTD) 400 in accordance with still another preferred embodiment of the subject invention. HTD 400 is similar to HTD 100, except that in HTD 400 the flow channel 404 is formed by a gap between the outer surface 410 of body 402 and a cylindrical surface 444 of an impeller 440. The impeller 440, which may have a shape of a cylinder is a rotatably suspended on bearings 442. Suitable bearings 442 may be formed as jewel bearings such as used in precision instruments. Alternatively, the bearings 442 may be formed as suitable friction-type or antifriction bearings. The cylindrical surface of the impeller 440 may be smooth or it may have grooves or dents to better engage the coolant 416 and to mix it. Suitable grooves may be circumferential, axial, crisscross, may form a pattern, or be random in size and/or
direction. Additional grooves may be added onto the flat sides of the impeller 440 to bring in coolant 416 and to allow formation of a lubricating film between the sides of impeller 440 and the body 402. The impeller 440 may be formed from metal, plastic, ceramic, glass, or other suitable material.

The impeller 440 may be rotated magnetically or it may be inductively coupled to external actuation means. For example, the impeller 440 may comprise a permanent magnet having a magnetization substantially in a radial direction of the impeller 440. The magnet may engage an external rotating magnetic field. Alternatively, the impeller may be driven by mechanical means via a suitable feed through.

The body 402 further comprises a first surface 406 adapted for receiving heat from a heat generating component (HGC), a second surface 408 adapted for rejecting heat. The flow channel 404 contains a liquid coolant 416. The coolant 416 preferably has a good thermal conductivity and low viscosity. This embodiment of the subject invention allows for using a broader range of coolant 416. For example, the coolant 416 may comprise substantially water, or alcohol, or mixture of water and alcohol, or Freon. The coolant 416 may also comprise a fluid containing nanometer-sized particles (nanoparticles) also known as nanofoam. Nanofluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids may be typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids may include water and ethylene glycol. Nanofluids may exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid.

In operation, external actuation means may be used to spin the impeller 440. Due to its finite viscosity, at least a portion of the coolant 416 is entrained by the cylindrical surface 444 and travels with it, thereby establishing a flow loop. If desired, the cylindrical surface 444 may have surface extensions (for example, ridges, grooves, or surface irregularities) to better entrain the coolant. Rotational speed of the impeller 440 may be used to control the velocity of the coolant 416. Thus, controlling the rotational speed of the impeller 440 allows to control the HGC temperature. This disclosure may refer to the means for flowing a coolant by a rotating impeller as an “impeller drive.”

Referring now to FIG. 19, there is shown an HTD 500 in accordance with a further preferred embodiment of the subject invention comprising a body 502 having a flow channel 504 with a flow diverter 565. This embodiment of the invention may be practiced with either the HTD drive, the magnetic drive, the inductive drive, or the impeller drive. For clarity, the drive is not shown in the figure. The flow channel 504 has a generally constant radius of curvature except for the flow channel portion in proximity of the HGC 114. In particular, in proximity of the HGC 114 the flow channel 504 includes the flow director 565 arranged to redirect the flow of the coolant 516 indicated by arrows 524 in a generally radial direction and to impinge into the channel wall just under the HGC 114. As a result, the heat transfer just under the HGC 114 may be substantially enhanced.

An alternative liquid metal alloy disclosed by Brandenburg et al. in the U.S. Pat. No. 7,726,972 and having reportedly extended useful temperature range may also be usable with the subject invention. The Brandenburg’s alloy differs from the commercially available Gallium-Indium-Tin (GaInSn) alloy in that its composition additionally includes 2%-10% Zinc (Zn). A preferred composition of the new alloy, referred to herein as GaInSnZn, contains approximately 3.0% Zn. Like the known alloy GaInSn, the new alloy GaInSnZn is liquid at ambient temperatures, but unlike GaInSn, the new alloy GaInSnZn has a substantially lower melting point. According to Brandenburg et al., the temperature scan analysis of the new alloy GaInSnZn exhibits a melting point of ~36 degree C., and experimental testing has shown that it operates satisfactorily in the subject apparatus at temperatures as low as ~40 degree C. A further advantage of the new alloy GaInSnZn relative to the known alloy GaInSn is that the constituent element Zinc is relatively low in cost compared to the other elements of the composition, thereby lowering the cost of the alloy, even as its melting point is significantly lowered.

While the preferred Brandenburg’s alloy composition includes 3% Zinc as described in the preceding paragraph, it should be appreciated that acceptable results for many liquid metal rotary connector applications may be achieved with a GaInSnZn alloy, where Zinc is present in a concentration range of 2%-10%. Also, alloys additionally containing up to 5% Bismuth (Bi) will provide acceptable results in the subject application. The Table I below sets forth three potential GaInSnZn alloy compositions, with Zinc present in concentrations of 3%, 5% and 7%, along with lower and upper ranges for each of the constituent elements.

<table>
<thead>
<tr>
<th></th>
<th>Ga</th>
<th>In</th>
<th>Sn</th>
<th>Zn</th>
<th>Bi</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Zn</td>
<td>66.4%</td>
<td>20.9%</td>
<td>9.7%</td>
<td>3.0%</td>
<td></td>
</tr>
<tr>
<td>5% Zn</td>
<td>65.1%</td>
<td>20.4%</td>
<td>9.5%</td>
<td>5.0%</td>
<td></td>
</tr>
<tr>
<td>7% Zn</td>
<td>63.7%</td>
<td>20.0%</td>
<td>9.3%</td>
<td>7.0%</td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>60%</td>
<td>18%</td>
<td>8%</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>Upper</td>
<td>70%</td>
<td>22%</td>
<td>12%</td>
<td>10%</td>
<td>5%</td>
</tr>
</tbody>
</table>

The HTD 200, HTD 300, and HTD 400 of the subject invention may also be practiced with a liquid coolant containing a volatile component suitable for boiling heat transfer. Such volatile components suitable for boiling heat transfer may include suitable fluorocarbon (Freon) refrigerant, ketone (such as acetone), or alcohol (such as ethanol or methanol), water, or ammonia. In this case, the coolant flow channel 204, 304, and 404 respectively may also include a void that is substantially free of liquid and may contain gases and/or vapors at a predetermined pressure. The void space allows for thermal expansion of the coolant and for formation of vapor bubbles from liquid coolant while avoiding excessive buildup of pressure inside the flow channel.

In operation, when the coolant suitable for boiling heat transfer receives heat, a portion of the high vapor pressure liquid undergoes nucleate boiling. Vapor bubbles are swept by the flow of coolant. Centrifugal force induces hydrostatic pressure within coolant, which may make the vapor bubbles buoyant. As a result, vapor bubbles may move away from the heat input surface and into the bulk flow of coolant, where they may collapse and deposit thermal energy.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," and "includes" and/or "including" when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or
more other features, integers, steps, operations, elements, components, and/or groups thereof.

The terms of degree such as “substantially”, “about” and “approximately” as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed. For example, these terms can be construed as including a deviation of at least ±5% of the modified term if this deviation would not negate the meaning of the word it modifies.

The term “suitable”, as used herein, means having characteristics that are sufficient to produce a desired result. Suitability for the intended purpose can be determined by one of ordinary skill in the art using only routine experimentation.

Moreover, terms that are expressed as “means-plus-function” in the claims should include any structure that can be utilized to carry out the function of that part of the present invention. In addition, the term “configured” as used herein to describe a component, section or part of a device includes hardware and/or software that is constructed and/or programmed to carry out the desired function.

Different aspects of the invention may be combined in any suitable way.

While only selected embodiments have been chosen to illustrate the present invention, it will be apparent to those skilled in the art from this disclosure that various changes and modifications can be made herein without departing from the scope of the present invention as defined in the appended claims. Furthermore, the foregoing description of the embodiments according to the present invention are provided for illustration only, and not for the purpose of limiting the present invention as defined by the appended claims and their equivalents. Thus, the scope of the present invention is not limited to the disclosed embodiments.

What is claimed is:

1. A heat transfer device comprising:
   a) a body having a first surface, a second surface, and a flow channel;
   b) said flow channel formed as a hollow cylinder inside said body;
   c) said hollow cylinder comprising an inner cylindrical surface and an outer cylindrical surface;
   d) said outer cylindrical surface having a central axis of symmetry, a first radius of curvature, and azimuthal direction;
   e) said inner cylindrical surface having a second radius of curvature and being substantially concentric with said outer cylindrical surface;
   f) said radii of curvature being substantially constant;
   g) said first surface of said body being in a good thermal communication with a heat generating component;
   h) said first surface of said body being generally tangential to said outer cylindrical surface with only a small separation between the two;
   i) said second surface of said body arranged to be in a good thermal communication with a heat sink;
   j) a liquid coolant substantially filling said flow channel; and
   k) a means for flowing said liquid coolant in said azimuthal direction.

2. The heat transfer device of claim 1, wherein said liquid coolant is electrically conductive and wherein said means for flowing said liquid coolant are selected from the group consisting of an MHD drive and an inductive drive.

3. The heat transfer device of claim 1, wherein said liquid coolant comprises a ferrofluid and wherein said means for flowing said liquid coolant comprise a magnetic drive.

4. The heat transfer device of claim 1, wherein said liquid coolant comprises substantially liquid selected from the group consisting of water, alcohol, Freon and nanofluid, wherein said means for flowing said liquid coolant comprise an impeller drive.

5. The heat transfer device of claim 1, wherein said liquid coolant substantially filling said flow channel does not entirely fill said channel and leaves a void space; said void space being filled by at least one of elastic material, crushable material, air, gas, and vapor.

6. The heat transfer device of claim 1, wherein said small separation between said first surface of said body and said outer cylindrical surface is less than 1 millimeter.

7. The heat transfer device of claim 1, wherein the difference between said first radius of curvature said second radius of curvature is less than 2 millimeters.

8. The heat transfer device of claim 1, further comprising a passage for a secondary coolant; said secondary coolant being in a good thermal contact with said second surface of said body.

9. The heat transfer device of claim 8, wherein said secondary coolant is arranged to flow in the direction generally transverse to the direction of flow of said liquid coolant.

10. The heat transfer device of claim 8, wherein said secondary coolant is arranged to flow in the direction generally opposite to the direction of flow of said liquid coolant.

11. A heat transfer device comprising:
   a) a body having a first surface, a second surface, and a flow channel;
   b) a liquid metal coolant substantially filling said flow channel; and
   c) a means for flowing said liquid metal coolant in said azimuthal direction;
   d) said flow channel formed as a cylindrical chamber inside said body;
   e) said cylindrical chamber comprising an inner cylindrical surface and an outer cylindrical surface;
   f) said outer cylindrical surface having a central axis of symmetry, a first radius of curvature, and azimuthal direction;
   g) said inner cylindrical surface having a second radius of curvature and being substantially concentric with said outer cylindrical surface;
   h) said radii of curvature being substantially constant;
   i) said first surface of said body being in a good thermal communication with a heat generating component;
   j) said first surface of said body being generally tangential to said outer cylindrical surface with only a small separation between the two;
   k) said second surface of said body arranged to be in a good thermal communication with a heat sink.

12. The heat transfer device of claim 11, further comprising:
   a) a permanent magnet generating a magnetic field within at least a portion of said liquid metal coolant;
   b) a ferromagnetic yoke; and
   c) a pair of electrodes for drawing electric current through said portion of said liquid metal coolant in a direction substantially perpendicular to the direction of said magnetic field.
13. The heat transfer device of claim 11, wherein said liquid metal coolant is substantially immersed in a magnetic field having a component that rotates substantially in said azimuthal direction.

14. The heat transfer device of claim 13, wherein the speed of rotation of said magnetic field component is in the range of 10 to 1,000 hertz.

15. The heat transfer device of claim 13, wherein said rotating magnetic field component is generated by an electromagnetic coil fed by polyphase alternating current.

16. The heat transfer device of claim 13, wherein said rotating magnetic field component is generated by a rotating permanent magnet.

17. A heat transfer device comprising:
a) a body having a first surface, a second surface, and a flow channel;
b) a liquid coolant substantially filling said flow channel; and
c) an impeller drive for flowing said liquid coolant in said azimuthal direction;
said flow channel formed as a cylindrical chamber inside said body;
said cylindrical chamber comprising an inner cylindrical surface and an outer cylindrical surface;
said outer cylindrical surface having a central axis of symmetry, a first radius of curvature, and azimuthal direction;
said inner cylindrical surface having a second radius of curvature and being substantially concentric with said outer cylindrical surface;
said radii of curvature being substantially constant;
said first surface of said body being in a good thermal communication with a heat generating component;
said first surface of said body being generally tangential to said outer cylindrical surface with only a small separation between the two; and

said second surface of said body arranged to be in a good thermal communication with a heat sink.

18. The heat transfer device of claim 17, wherein said liquid coolant comprises substantially of liquid selected from the group consisting of water, alcohol, Freon and nanofluid.

19. The heat transfer device of claim 17, further comprising an impeller having a cylindrical surface substantially inside said flow channel and concentric with said outer cylindrical surface; said impeller arranged to rotate about said central axis of symmetry.

20. A method for transferring heat from a heat generating component to a heat sink comprising the steps of:
a) providing a body having a first surface, a second surface, and a cylindrical chamber;
said cylindrical chamber formed within said body;
said cylindrical chamber comprising a cylindrical surface having a central axis of symmetry, a constant radius of curvature, and azimuthal direction;
said first surface being in a good thermal communication with a heat generating component;
said second surface being in a good thermal communication with a heat sink;
b) providing a liquid coolant substantially filling said cylindrical chamber; said liquid coolant being selected from the group consisting of ferrofluid and electrically conductive liquid;
c) providing a drive means for flowing said liquid coolant in said cylindrical chamber in the azimuthal direction of said cylindrical surface; said drive means selected from the group consisting of an MHD drive, inductive drive, magnetic drive, and impeller drive;
d) receiving heat from said heat generating component;
eg) transferring heat to said coolant;
h) flowing said liquid coolant in said azimuthal direction;
and
i) transferring heat from said liquid coolant to a heat sink.

* * * * *