

HEAT CAPTURE, TRANSFER AND RELEASE FOR INDUSTRIAL APPLICATIONS

[0001] This invention relates to the field of thermal energy capture, transfer, and release in applications, such as thermal treatment for enhanced oil recovery (EOR), heating underground geological deposits, recovering heat from geothermal sources, and efficiently transferring heat in multiple industrial applications. In particular, embodiments of the invention relate to systems and methods of capturing, transferring, and releasing thermal energy from intermittent sources (such as metallurgical operations), continuous sources at high temperature (such as chemical and petro-chemical operations) and continuous sources at low temperature (such as waste heat sources). A key feature of the invention is the ability to transfer heat over short or long distances with minimal heat and temperature losses. The invention also includes methods of manufacturing devices for the capture, transfer and release of heat energy, and methods to install such devices in numerous industrial applications.

BACKGROUND

[0002] In most industrial situations, heat capture involves the transfer of such energy from hot gases, liquids, or solids into other media that either conduct heat away via thermal conductivity, as is the case of heat exchangers, phase-change involving evaporation or melting, as is the case of quenching reactions, or by convection or radiation. However, in many industrial systems heat is mainly dissipated rather than captured by conduction, convection or radiation. For example, melting and quenching operations, such as the quenching of hot metallurgical coke with water, seldom capture the radiation or the steam produced, so the heat is dissipated but not captured. Most heat capture operations in industry rely on the thermal conductivity of a metal or other material that encapsulates the heat producing medium. This metal or other material subsequently transfers the heat away from its source. Therefore, a critical parameter in heat capture is the thermal barrier presented by the encapsulating material. This thermal barrier is also a critical parameter in the eventual release of heat.

[0003] When the heat is captured, methods of thermal transfer over distance normally rely on either insulated steam pipelines or the transfer of heat via thermal fluids which may include oil-based fluids, such as DowTherm®, eutectic mixtures such as molten salts, molten metals such as Na, or Pb, or Sn (these may be appropriate for metallurgical applications), or

molten alloys. Steam is usually preferred in most industrial applications because it provides a considerable amount of heat upon condensation, it is often the low cost option and is easily pumped over some distance. However, heat losses in moving steam are also quite significant in spite of insulation, and so the distance over which steam can be economically transferred is necessarily limited. The same is true of thermal fluids with the aggravating feature of the additional weight and costs involved. In the case of molten salts, the entire pipeline would require replacement if the salt were allowed to “freeze” in place, a problem that has often occurred.

[0004] In addition to the above limitations and parameters, some industrial applications present unique problems to the capture, transfer, and release of heat, and deserve further discussion.

Heat transfer in Enhanced Oil Recovery

[0005] In conventional oil production, oil is recovered from oil bearing salt domes by drilling. Since the typical oil formation is under pressure, initial production is facilitated by the flow of oil to the surface under pressure. Over time, such natural flow decreases as the pressure declines, and production relies on enhanced oil recovery methods. These methods may include pressurization by injecting CO₂, water flooding, or heating with steam. Steam injection has become popular, because (a) the increase in temperature caused by the steam decreases the fluid viscosity of the oil, (b) the water that condenses underground also displaces the oil while increasing underground pressure, and (c) the dual phase flow may reduce overall flow viscosity.

[0006] As conventional oil deposits are exhausted, oil production is increasingly relying on oil shales and similar formations that are generally less porous and more difficult to access. Such oil sources are generally subjected to hydraulic fracturing, otherwise known as “fracking,” where water pulses at great pressure are used to fracture underground rocks so as to enhance porosity, thus allowing the flow of hydrocarbons (natural gas or oil) to the surface. Over time, a similar decrease in the flow of hydrocarbons occurs as underground pressure declines with production, and similar EOR methods are employed: water, CO₂, or steam injection. All such methods are energy intensive and costly. There is a need for EOR methods that are energy efficient and that do not require vast amounts of water for either injection or steam production.

Heat transfer from Geothermal fields

[0007] Unlike the case of enhanced oil recovery where the problem is to get heat down to the oil below the surface, geothermal fields have thermal energy already below the surface, and therefore heat can flow from the bottom to the top of a heat pipe or thermosyphon, while the working fluid from the top to the bottom either by gravity, through a wick, or by both. Thus, the key impediment to the use of heat pipes in geothermal applications is the distance of the heat transfer, that is, the practical length needed for the heat pipe or thermosyphon.

Heat transfer in Industrial Applications

[0008] Most industrial applications involve operating plants where facilities are distributed in a fairly level field sometimes covering several acres and numerous production units. Thermal energy in such facilities is normally available where exothermic reactions take place, in boiler houses, furnaces, and the like, whereas thermal energy may be required at some distance from those facilities. Thus, heat transfer at industrial plants primarily involves horizontal transfer over hundreds or a few thousands of feet, but normally does not entail transfer over a significant vertical distance.

[0009] Heat pipes, with their outstanding heat flux rates due to internal mass transfer of vapor, are well suited to horizontal heat transfer because there is no significant limitation of capillary action over distance. Thus, the main practical limitation for this type of application stems from the length of commercially available heat pipes.

SUMMARY

[0010] Embodiments of the present invention provide novel means for capturing, transferring, and subsequently releasing heat that can be applied to industrial applications, such as thermal treatment for enhanced oil recovery (EOR), heating underground geological deposits, recovering heat from geothermal sources, controlling temperature in chemical processes, capturing and reusing waste heat in plants and factories, and efficiently transferring heat in a wide variety of other industrial applications. In particular, embodiments of the invention relate to systems and methods of capturing, transferring, and releasing thermal energy from intermittent sources (such as metallurgical operations), from continuous sources at high temperature (such as chemical and petro-chemical operations), and from continuous sources at low temperature (such

as waste heat sources). A key feature of the invention is the ability to transfer heat over short or long distances with minimal heat and temperature losses. The invention includes methods of manufacturing devices for the capture, transfer and release of heat energy, and methods to install such devices in numerous industrial applications. The invention allows for the rapid transfer of heat at temperatures in the range of -40 °C to 1300 °C, or more, from a variety of heat sources, and the subsequent release of such heat at variable or constant temperature for a long period of time. The system includes a novel heat pipe that is thermally insulated over most of its length. In some embodiments, the low end of the temperature range can be 0, 50, 100, 150, 200, and 250 degrees. The upper end of the temperature range can be 1500 or more, 1400, 1300, 1200, 1100, 1000, 900, 800, 700, 600, 500, 400, and 300 degrees. In embodiments of the system, the dimensions of the heat pipe, the type of thermal insulation, the fabrication method, and its placement in the field are determined by the conditions and characteristics of each industrial application, by the demand of heat transfer in terms of heat release, and by the type of thermal energy available.

[0011] Some embodiments of the invention provide a heat management system that can include a plurality of heat transfer devices that can include, for example, conventional heat pipes, advanced heat pipes, thermosyphons, heat spreaders, pulsating or loop heat pipes, steam pipes, and the like, assembled into an entity providing continuous thermal communication, adapted to capture, transfer, and release heat at temperatures in the range of -40 °C to 1,300 °C at a distances of from 0.1 m to 14 km, with a temperature loss from capture to release between 0% and 40% of a temperature at a source of the heat to be transferred, wherein the heat thus can be transferred from one or more heat sources, and wherein the heat transfer devices can capture or provide heat for at least one application. In some embodiments of the invention, the distance can be from 0.3m, 1m, 3m, 10m, 30m, 100m, 300m, 500m, and 1km to 2km, 3km, 4km, 5km, 6km, 7km, 8km, 9km, 10km, 11km, 12km, 13km, 14km, or more. Likewise, in some embodiments of the invention, the temperature loss or heat loss can be 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, and 9% at a low end and 12%, 15%, 20%, 25%, 30%, 35%, or 40%, or more. Acceptable temperature loss can depend upon the circumstances of the particular use of the system. In some situations, a very low heat loss is particularly advantageous and may be required in order for a particular application to be cost-competitive. In other situations, where the competing technologies are ineffective or inoperable, a larger amount of heat loss or temperature loss can be

acceptable and can be highly competitive with any alternative available. Accordingly, the desired or market-required degree of minimization of heat loss can be relative to competitive alternatives.

[0012] In other embodiments, the heat management system can include one or more heat transfer devices that can include, for example, conventional heat pipes, advanced heat pipes, thermosyphons, heat spreaders, pulsating or loop heat pipes, steam pipes, or the like, and can also include a combination of such heat transfer devices, assembled into an entity that can provide continuous thermal communication adapted to capture, transfer, and release heat at temperatures in the range of -40 °C to 1,300 °C at a distance of from 500 m to 14 km with a temperature loss from capture to release between 0% and 40% of a temperature at a source of the heat to be transferred, wherein the heat thus can be transported from one or more heat sources, and wherein the heat transfer devices can capture or provide heat for at least one application.

[0013] In other embodiments, the heat transfer devices of the system can have one or more wicks. In some embodiments, the heat transfer devices can have no wicks. In some embodiments, the heat transfer devices can include an encapsulating material manufactured from, for example, steel, copper and its alloys, titanium and its alloys, aluminum and its alloys, nickel and chromium alloys, wound metal foils, wire screens, scaffolds, and the like, or any combination thereof. In other embodiments, the heat transfer device can include different metals and alloys that can include varying thermal conductivities.

[0014] In other embodiments, the heat transfer devices of the system can include multiple sections such as, for example, evaporators, heat transfer sections, and condensers, or the like. In some embodiments, the sections can include a wick characteristic such as no wicks, full wicks, partial wicks, and the like, or any combination thereof.

[0015] In further embodiments, the application of the system can include, for example, power plants, geothermal energy production, enhanced oil recovery, gas recompression, water desalination, metallurgical processing, chemical and petrochemical operations and production, pulp and paper industries, plastic and rubber operations, refractory industry, glassmaking operations, mining operations, plywood and oriented strand board manufacturing,

fermentation, fertilizer production, industrial gas production, military applications, solar energy production, rubber manufacturing, oil refineries, and the like.

[0016] In additional embodiments, the encapsulating material of the heat transfer devices can include, for example, a metal, plastic, or ceramic composition, or a composition combining such components, that can be non-reactive with respect to the variety of heat sources, non-reactive with respect to a heat transfer medium, and non-reactive with respect to the heat source.

[0017] In other embodiments, different individual wicked heat transfer devices can be joined so a joined wick structure can exist, having continuity compatible with capillary action along the length, the continuity can permit thermal communication of internal working materials throughout the length, and the internal working materials include, for example, fluids, solids that sublime, materials having multiple chemical hydration levels, and the like, as well as any combination thereof.

[0018] In other embodiments, the wick structure can include multiple layers having different porosities. In further embodiments, the wick structure can include an internal wick structure that can include an axial wick. In other embodiments, the wick structure can include materials such as, for example, sintered metals, metal screens, grooves, oxides, borates, solids that sublime, materials with different chemical hydration levels, nano-particles, nanopores, nanotubes, and the like.

[0019] In additional embodiments, different materials can be used at different positions along the length, and the materials can be selected to optimize heat capture and release, while minimizing heat loss.

[0020] In other embodiments, the wick can be formed, for example, by spraying, painting, baking, PVD, CVD, pyrolysis of organic compounds, or the like. In some embodiments, the wick can be formed by thermally decomposing a slurry of metal particles in a liquid metal precursor and/or by similar processes.

[0021] In some embodiments, the encapsulating tube can include a wound strip of foil or the like; the foil can be thin in some embodiments.

[0022] In additional embodiments, the wound strip structure can be pre-coated with wick material before being formed into tubular assemblies around, for example, metal scaffolds or the like that can include, for example, mesh screens.

[0023] In some embodiments, any gaps in the wound tube can be sealed by a separate wound strip or the like.

[0024] In some embodiments, the amount of working material can be in excess of what is needed to saturate the internal wick structure.

[0025] In some embodiments, the working material in the heat transfer devices can have a phase change temperature in the range of -40 °C and 1,300 °C, or more.

[0026] In some embodiments, the heat transfer device can include at least one valve proximate to at least one end in order to control and maintain partial vacuum.

[0027] In some embodiments, vertical heat transfer devices of up to 14km in length can be installed in a manner to prevent the physical degradation or breakage of the heat transfer devices. In such embodiments, the weight of the heat transfer device is neutralized by, for example, at least one buoyant balloon, at least one helicopter, a combination thereof, or the like.

[0028] In various embodiments, the heat transfer devices can be installed using at least one installation aid such as a crane, a helicopter, a balloon, a wheel, an oil rig, a tower, or the like. In some embodiments, heat transfer devices of, for example, 3-7 Km in length can be installed without physical degradation or breakage of such heat transfer devices, and the heat transfer device can be wound around a wheel of, for example, 100-500 feet in diameter that minimizes the curvature of the heat transfer device. In some embodiments, the heat transfer devices can be insulated.

[0029] In some embodiments, pulsating heat pipes can be made by encapsulating a thin metal or alloy layer in, for example, a strong metal screen or the like, to resist pressure pulses.

[0030] Some embodiments of the invention can include a method of heat capture, transfer and release using a heat management system.

[0031] Some embodiments include methods for manufacturing a heat management system that can include the steps of: selecting the type of heat transfer device from, for example, conventional heat pipes, advanced heat pipes, thermosyphons, spreader heatpipes, loop heat pipes, pulsating heat pipes, steam pipes, any such combination, or the like; selecting a method of joining heat transfer device elements from, for example, soldering, brazing, welding, threading, foil winding, mechanical fittings, encapsulating thermal fluids, any combination, or the like; selecting a type of wick structure from, for example, sintered metal, axial wick, metal screens, grooves, any combination, or the like, or no wick material; selecting the internal working material from, for example, aqueous solutions, eutectic salt mixtures, organic thermal fluids, or high-temperature metals and alloys that can liquefy at temperatures in the range of -40 °C to 1,300 °C, solids that sublime, or materials with different chemical hydration levels; and additionally the methods can include applying the joining method, wick structure, and working fluid thus selected; and sealing the heat transfer device under vacuum.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0032] FIG 1 Shows a possible power plant configuration.
- [0033] FIG 2 Shows a ductwork configuration.
- [0034] FIG 3 shows aerodynamic shapes of heat pipes to minimize drag forces.
- [0035] FIG 4 Illustrates a ductwork configuration for minimal pressure drop.
- [0036] FIG 5 Shows an optional configuration for heat recovery from a baghouse.
- [0037] FIG 6 Shows an optional configuration for heat recovery from an electrostatic precipitator (ESP).
- [0038] FIG 7 shows an optional heat capture configuration from intermittent heat sources.
- [0039] FIG 8 Shows a ductwork configuration for heat storage.

[0040] Figure 9 Shows two optional configurations for recovering heat from the Bayer Process.

[0041] FIG 10 illustrates a cross sectional view of an embodiment of a heat transfer method for EOR.

[0042] FIG 11 is a cross sectional view of an embodiment describing the installation of a heat transfer device for EOR.

[0043] FIG 12 shows an alternative embodiment of an installation method of heat transfer device for EOR.

[0044] FIG 13 illustrates embodiments of heat transfer devices for geothermal installations.

[0045] FIG 14 shows and alternative embodiment of a heat transfer device for industrial plants.

[0046] FIG 15 are diagrams of a heat transfer devices with a thermal insulation.

[0047] FIG 16 illustrates a cross sectional view of a heat pipe.

[0048] FIG 17 is a schematic view of a high-performance heat pipe.

[0049] FIG 18 illustrates two schematic diagrams of heat pipes.

[0050] FIG 19 illustrates an alternative embodiment for long distance heat transfer.

[0051] FIG 20 is a diagram of a method for making long heat pipes.

[0052] FIG 21 is a cross sectional view of an alternative embodiment of a winding strip with a porous capillary surface.

[0053] FIG 22 illustrates an alternative embodiment for making long heat pipes.

[0054] FIG 23 illustrates an embodiment of an axial wick for heat pipes.

[0055] FIG 24 illustrates an embodiment for maintaining internal vacuum in heat pipes.

[0056] FIG 25 shows an alternative embodiment for making advanced heat pipes.

[0057] FIG 26 shows an alternative embodiment for ultra-long advanced heat pipes.

[0058] FIG 27 illustrates a heat pipe joining method.

[0059] FIG 28 illustrates a method for interrupting heat transfer in a complex heat pipe.

[0060] FIG 29 is a schematic of a heat transfer device.

DETAILED DESCRIPTION

Definitions

[0061] Thermal energy or heat (in common usage) represents the thermal energy of molecules, atoms or ions including kinetic, vibrational and rotational forms of energy. Heat also represents the transfer of kinetic energy from one medium or object to another, or from an energy source to a medium or object. Such energy transfer can occur in three ways: radiation, conduction, and convection but here will be used in a general common sense to include available thermal energy content. Some believe heat refers to the *transfer* of energy between systems (or bodies), not to energy contained within the systems, but this understanding is unnecessarily restrictive. Others define heat as the form of energy that flows between two samples of matter due to their difference in temperature, and that is also restrictive. The following definitions of heat are useful:

- a. A form of energy associated with the motion of atoms or molecules and capable of being transmitted through solid and fluid media by conduction, through fluid media by convection, and through empty space by radiation.
- b. The transfer of energy from one body to another as a result of a difference in temperature or a change in phase.
- c. Thermal energy either latent or sensible.

[0062] “Heat transfer devices” (HTDs), in the context of the current invention, include conventional and novel HP, spreader HP, thermosyphons, steam pipes, and pulsating heat pipes. When heat pipes are mentioned as the method of heat capture, transfer and release, pulsating heat and pipes spreader heat pipes can also be used. In vertical applications, thermosyphons can be used in place of heat pipes. Heat pipes are devices that can capture, transfer, and deliver heat more effectively than heat exchangers, metal surfaces, or thermal fluids because they operate on two physical principles and not just on thermal conductivity. During heat capture and release, heat pipes rely on both thermal conductivity and phase change, but the latter is several times more effective than the former, so the overall thermal performance is many times better than a comparable heat exchanger with similar surface area in the applications under discussion. Furthermore, during heat transfer, the ability of a heat pipe to transfer heat by mass transfer is, again, many times greater than the speed of thermal conductivity alone, even when dealing with highly conductive materials such as copper or silver. The superior performance of heat pipes over thermal fluids in the applications under discussion stems from the difference in specific heats of a common working fluid in heat pipes—water—versus the heat capacity of organic liquids in the case of thermal fluids.

[0063] An important feature of HTDs described in the current invention is the superior heat transfer mechanisms of the heat pipes. As shown in subsequent paragraphs, heat pipes provide a means of transferring heat that is near thermodynamically reversible, i.e., a system that transfers enthalpy with almost no losses in efficiency. Furthermore, while conventional heat pipes share these unique mechanisms, the advanced heat pipes described herein are characterized by significantly improved heat capture, transfer, and release performance and, thus, by approaching a thermodynamically reversible process even closer.

[0064] There is a need for an inexpensive heat-transfer mechanism that can readily transport heat at elevated temperature from surface operations, that can deliver such heat at constant temperature over a long period of time to underground formations, that requires little or no maintenance, that is reliable, and that requires minimal water or steam for operation.

[0065] Commercially available heat pipes come in lengths of a fraction of an inch to several feet, but not in hundreds or thousands of feet, and there is a reason for that. As explained in sections of the detailed description, below, an essential aspect of a heat pipe is its ability to

circulate the condensed working fluid back to the hot area of the heat pipe. That ability is quite difficult to accomplish with current manufacturing processes, because a) capillarity forces in the current HP would not be able to lift the liquid hundreds of feet and, b) any interruption in the internal capillary action would also interrupt the internal transfer mechanism. Therefore, there is a need for long heat pipes that can be made to function effectively.

Heat capture using heat pipes, spreader heat pipes, thermosyphons, and pulsating heat pipes

[0066] Figure 29 is a schematic of a heat transfer device, for example a type of heat pipe. In FIG 29 the heat pipe (4) is composed of three major sections: a heat capture section (4'), a heat transfer section (4''), and a heat release section (4'''). The heat transfer section is normally called the “adiabatic” section because heat losses are so small that they are normally ignored, so the term adiabatic is used, although heat losses in adiabatic processes are never really zero.

[0067] Embodiments of the invention are disclosed herein, in some cases in exemplary form or by reference to one or more Figures. However, any such disclosure of a particular embodiment is exemplary only, and is not indicative of the full scope of the invention.

[0068] Industrial heat capture entails: (a) the capture of waste and/or low-grade thermal (heat) energy, such as hot flue gases, (b) cooling of various industrial and chemical processes, such as those that include exothermic reactions, (c) controlling temperature in certain chemical or petrochemical plants, such as controlling the oxidation of propylene oxide at 200 °C during the production of propylene glycol, (d) using heat capture for delivery at remote locations, such as in enhanced oil recovery (EOR), and (e) capturing heat from difficult to access locations, such as tapping geothermal sources. Applicants review these by means of examples that illustrate the broad scope of the invention in various applications.

Capturing Waste, Low-, and High-Grade Thermal Energy

[0069] These industrial applications normally encompass large amounts of heat at temperatures that range from about 60 °C to perhaps as high as 250 °C which hinders the utilization of such energy for other heat consuming applications, such as additional power generation. The industries that generate large amounts of low-grade heat include but are not

limited to (a) those that use large amounts of fuel and generate large amounts of flue gases, such as power plants, especially coal-fired plants, metallurgical and cement plants, and that dispose of those flue gases by means of stacks or chimneys (b) those that use industrial kilns, calcination furnaces, or process reactors, such as lime producers, alumina producers, magnesia producers, and many inorganic chemical producers (c) those that generate large amounts of heat without flue gases, such as nuclear power plants, compressors, power transformers, refractory plants, glassmaking plants, or thermal power plants with their large heat producing condensers.

[0070] Since fuel combustion constitutes a large fraction of energy generation from industry, capturing heat from flue gases becomes a relevant application for many industries. The recovery of heat from the flue gas of coal-fired power plants is selected to illustrate heat capture methods and mechanism.

[0071] Figure 1 illustrates a typical configuration for recovering heat from such flue gases. In Figure 1, the cross section of a typical flue gas duct (52) is a rectangular cross section measuring about 20x30 feet. A number of heat pipes (4) penetrate the section of the flue gas (52). The heat pipes are in contact with the flue gas, which is at temperatures of 300 °F to 450 °F, and capture a fraction of the available heat in the gas. Capturing only a fraction of the available heat is an important feature in this particular application, because the temperature of the flue gases cannot be allowed to drop excessively. Such a drop would impair the eventual flow of flue gases through the disposal chimney. The heat pipes (4) that capture heat are connected to a larger and more complex heat pipe (58). This heat pipe has a larger diameter and, thus, greater capacity for transferring large amounts of heat. Alternatively, one can use different wick structures that are more efficient at long distances. The larger diameter heat pipe (58) transfers the captured heat to another location where such heat is fed into a set of smaller diameter heat pipes (4) which in turn deliver such heat to a process vessel (53) that requires heat, such as, for example, the heat input section of a water purification system. Thus, an important function of heat capture involves using heat pipes that can transfer heat from the flue gases and deliver it to other processes that are at a distance from the original flue gas heat source.

[0072] Figure 2 illustrates optional configurations for inserting heat capture devices into ductwork. As shown in figure 2, the heat capture devices (4) (e.g., conventional heat pipes, thermosyphons, spread heat pipes, or pulsating heat pipes) are inserted part way into the cross

section of the flue gas duct (52) either vertically as illustrated in Figure 2(a) or horizontally as shown in Figure 2(b). In preferred configurations, heat pipes are placed co-linearly with the direction of flow of the flue gases so as to minimize the drag forces and, thus, the pressure drop in the flue gas and potential erosion of the HP. Optionally, heat pipes can be alternated between the vertical and horizontal direction, or at intermediate insertion angles. In addition, heat pipes can be placed adjacent or staggered to each other to minimize turbulence and pressure drop and the thickness of boundary layers so as to maximize heat transfer from the bulk of the gas to the surface of the heat pipe.

[0073] Figure 3 illustrates another feature of heat pipes that is useful for minimizing drag in fluid flow: the thermal performance of a heat pipe is independent of the cross-sectional shape of the heat pipe, that is, the transfer of heat is primarily dependent on the cross sectional area and the surface area of the heat pipe, and far less on whether the cross-section is circular, rectangular, or another shape as long as the thickness of the gas boundary layer and residence times are similar. Figure 3 shows a cross section of the flue gas duct (52) with a series of heat pipes (4) with cross sectional shapes that are aerodynamically designed to minimize drag, boundary layer thickness and maximum contact time. Thus the leading heat pipe (4) has a different cross-section than the last heat pipe (4') in the row.

[0074] Figure 4 illustrates another method for minimizing drag in fluid flow. In Figure 4, the heat pipes (4) are inserted at an angle with respect to the direction of flue gas flow. Normally, drag forces and erosion are minimized when this angle is about 30° from the direction of flow, although other angles may be preferred depending on the configuration of the ductwork.

[0075] Typically in a coal fired power plant, the combustion gases are first subject to catalytic denitrification by means of ammonia or amines, then ash in the flue gases is reduced by either filtration in a baghouse or electrostatic precipitation. Subsequently, the flue gases are conveyed by means of the flue duct into a fan that increases the pressure prior to flue-gas desulfurization (FGD). Following FGD, the flue gases are vented to the atmosphere by means of a stack or chimney, which is another point of potential capture for low-grade heat. Figure 5 shows an alternative configuration for capturing heat directly from ductwork in a coal fired power plant, that is, capturing heat at the baghouse (66). In Figure 5, the heat pipes (4) are placed inside (the clean side) the filters of the baghouse (66) in order to minimize ash deposition onto

the heat pipes. The flows of the flue gas and the flows of the fluid inside the heat pipes will be parallel and concurrent. The hot gas will contact the heat pipe and heat captured at the bottom of the heat pipe, will be rapidly transferred outside the baghouse area, which will initiate cooling of the flue gas. The total pressure drop of the flow in the filter bag will be proportional to the inverse of the free cross-sectional area inside the bag. For a 1 cm diameter heat pipe inside a 10 cm diameter ceramic filter, the additional pressure drop due to the heat pipe will be: $10^2/(10^2 - 1^2) - 1$ or approximately a 1 % extra pressure drop. If one places 6 heat pipes, one still has $10^2/(10^2 - 6 \times 1^2) - 1$ or approximately a 6% increase in pressure drop, which is within the margins of fluctuation of the flue gas system. The number, distribution and diameter of heat pipes will be determined by the dimensions of the filter bags and the desired fraction of heat to be recovered.

[0076] Figure 6 shows still another optional configuration for capturing heat directly from ductwork in a coal-fired power plant, that is, capturing heat at the electrostatic precipitator (67). The electrostatic precipitator system is designed to have maximum area of contact with the flue gas to be able to charge most of the particles flowing by with a minimum pressure drop. Therefore, the contact gas-solid contact is already good. A preferred configuration is to make the perforated plates (see Figure 6) to be heat pipes. The plates already have connection to the external electrical powering system, so the across the roof connections could also be used as heat transfer conduits, the HP themselves. Figure 6 illustrates the proposed configuration in an electrostatic precipitator. Since no changes in the flue gas flow are considered, the pressure drop in this particular configuration would be that of the electrostatic precipitator without any further increase.

[0077] The benefits of these last two configurations—capturing heat at the baghouse or at the electrostatic precipitator—are twofold: first heat is captured at a slightly higher temperature than in the flue-gas duct thus improving thermal efficiency, and second each of these process units can be used to perform dual functions, their original function and the additional heat capture function. Note also that since with the use of HP, the electrostatic precipitator will be kept at a lower temperature than in the conventional mode and as consequence it will attract more and even finer particles driven by thermo-foretic forces thus further enhancing the filtering action.

[0078] Industrial operations that generate large amounts of heat intermittently constitute a special case. Those operations occur in such industries as integrated steel plants that utilize oxygen converters, secondary steel plants that use electric furnaces, and non-ferrous plants that produce metals like copper, lead, silicon, or titanium. The processes in these plants all generate large amounts of heat at very high temperatures but not necessarily continuously. The capture of this type of intermittently produced heat is similar to previous examples described above, but the transfer and release of such heat presents restrictions that are not found in continuous heat sources. One option is to capture heat for use in applications that also operate intermittently. Another is to store the intermittent heat in a separate vessel filled with a thermal fluid: DowTherm® or equivalent for medium to low temperatures, molten salts or eutectics for higher temperatures, or advanced heat storage systems, such as “Heat Transfer Interphase,” filed 12 January of 2011, with priority date of 12 January of 2010, and with the International Application Number of PCT/US2011/021007, and assigned to Sylvan Source, Inc, which is incorporated by reference in its entirety.

[0079] Thus, it is clear that there is a dual industrial need: (a) the need for novel heat pipes that capture, transfer, and release thermal energy over long distances, including vertical distance, and (b) the need for storing thermal energy from high-temperature sources that are intermittent. The combination of such dual features opens up multiple industrial applications that are not possible otherwise.

[0080] Figure 7 illustrates heat capture from an oxygen converter, which is normally used in integrated steel plants, as well as in copper and lead plants. In Figure 7, an oxygen steel converter (71) contains molten iron (72) saturated with carbon and covered by a thin layer of slag (73). Oxygen gas is blown into the molten iron by means of an oxygen lance ((74) for periods on the order of 20 to 30 minutes and, during this operation, copious amounts of combustion gases (75) containing CO and CO₂ evolve at very high temperature, higher than 1,500 °C. Such combustion gases (75) are collected above the converter by a hood (76) and carried away by a metal duct (77). The duct is enlarged in order to fit a number of heat pipes (4) that capture part of the heat and transfer it to a storage tank (54) filled with a thermal fluid that may include molten salts or eutectics that are stable at those temperatures. Suitable compositions for those

molten salts and eutectics are described in South African Patent No. 2012/05975, Issued on May 29, 2013.

[0081] Figure 8 illustrates another example of heat storage, but one that applies to continuous heat generation. Figure 8 shows an optional configuration for capturing and transferring heat from the ductwork (52) of a power plant into a storage vessel (54) that allows interruption of heat transfer by simply opening valve (56) thus draining the thermal storage tank into a lower vessel (55). When the thermal fluid is in the lower vessel, heat is no longer being captured from the ductwork. The thermal fluid is stored until it is needed again to capture more heat, at which point pump (57) activates and the thermal fluid is pumped up to the vessel (54) and again allowed to come in contact with the heat pipes (4). In addition, the thermal fluid tank (54) allows a large-diameter heat pipe (58) to capture the heat of the thermal fluid so it can be transferred away for potential use, such as in water purification.

Cooling of Industrial and Chemical Processes

[0082] Numerous industrial applications require capturing heat as a means of cooling and refrigeration. Such industries include but are not limited to icemaking, brewing, underground mining, pulp and paper manufacture, food processing, beverage production, dewatering during biofuel production, and the cooling of chemical and petrochemical reactions that are exothermic such as in the production of cellulose acetate, nitrobenzene, polyvinyl-chloride resins, carbon disulfide, cumene (from alkylation of benzene with propylene), ethyl alcohol (from hydration of ethylene), formaldehyde (from methanol using exothermic reactor), phenol (from cumene peroxidation), and propylene glycol (by hydration of propylene oxide at 200 °C), acrylic resins (from catalytic oxidation of methyl methacrylate), aromatic ketone polymers (from condensation polymerization reactions), copolyester-ether elastomers, and polyacetal resins, to name a few.

[0083] Many industrial cooling operations employ double walled reactors where the outer vessel contains a circulating coolant, such as water or a thermal fluid, that takes away excess heat from the inner reactor, thus preventing run-away reactions from exothermic operations. Figure 9 illustrates a typical double-walled reactor for cooling, and while the example covers the digestion of bauxite into sodium aluminate as a first step in making alumina, it could also cover many double-walled reactors used for cooling industrial processes. In Figure 9, two alternative configurations are presented. Figure 9(a) illustrates a conventional double-wall

reactor, where the outer vessel (64) is filled with a thermal cooling fluid (typically water), and surrounds the inner reactor (63) where bauxite is digested with caustic (NaOH). The reactor top (65) closes the reactor and maintains pressure and temperature. The thermal fluid is kept circulating by pump (57), while a heat pipe (4) conducts heat away from the thermal fluid for possible use elsewhere.

[0084] Figure 9(b) illustrates an alternative embodiment where the outer vessel is replaced by a cylindrically shaped heat pipe (4) that contains a capillary wick (12) throughout its entire inner surface area, thus accelerating the capture of heat and its transport away from reactor. This type of complex heat pipe (58) is discussed in subsequent paragraphs. In cooling applications the working fluid of the heat pipe need not be water or aqueous fluids, but can be cryogenic fluids, such as ammonia and the like. Other alternative configurations for capturing heat in cooling and refrigerating applications are covered in South African Patent No. 2012/05975, Issued on May 29, 2013, which is hereby incorporated by reference in its entirety.

[0085] Cooling towers are generally used for cooling excess heat in thermal power plants and are commonly employed throughout the chemical and petrochemical industry. Cooling towers dissipate heat by evaporation and therefore, substantially contribute to water losses in an industrial operation. Heat pipes can be used for the augmentation and replacement of cooling towers because of their superior performance in capturing, transferring, and releasing heat. Thus, heat pipes can capture heat from fluids (gases or liquids) before they enter the cooling tower, thus augmenting the capacity of the cooling tower and, if sufficient heat is captured the cooling tower may be eliminated altogether.

Controlling Temperature in Chemical or Petrochemical plants

[0086] Many chemical and petrochemical industries require precise control of operating temperature. In this invention, the means of controlling temperature are similar to those considered in Figure 9 above, where cooling is done in double-walled reactors. Industries requiring close temperature control include but are not limited to acetaldehyde (from oxidation of ethylene), acetic acid (from carbonilation of methanol), acetone (from catalytic dehydrogenation of isopropyl alcohol), acrylic acid (from propylene oxidation), acrylonitrile (from ammoxidation of propylene), adipic acid (from cyclohexane oxidation), plasticizer alcohols (from hydroformilation of olefins), alkyl amines (from alcohol/ammonia reactions), benzene (from

hydrodealkylation of toluene, 1-4 butanediol (from acetylene/formaldehyde reaction), carbon disulfide (from natural gas and sulfur reaction), carbon fibers, carboxymethylcellulose (CMC), cellulose acetate and tri-acetate fibers, chlorinated isocyanurates (from urea pyrolysis), C2 chlorinated solvents (from chlorination of ethylene dichloride), chlorinated methanes, cumene (from alkylation of benzene with propylene), cyclohexane (from hydrogenation of benzene with hydrogen), di isocyanates and polyisocyanates (from phosgenation of primary amines), ethyl alcohol (from hydration of ethylene), ethyl benzene (from the alkylation of benzene by ethylene), ethylene dichloride (from reacting ethylene with oxygen and hydrogen chloride), ethylene oxide (from oxidation of ethylene), formaldehyde (from methanol using exothermic reactor), hydrogen cyanide, isopropyl alcohol (from hydration of propylene with superheated steam), ketene/diketene (from vapor-phase cracking of acetic acid), linear alkylate sulfonates (from sulfonation of linear alkyl benzene with oleum or with sulfur trioxide in sulfuric acid), linear alpha olefins (from ethylene oligomerization), maleic anhydride (from vapor-phase oxidation of hydrocarbons), methanol (from synthesis gas and carbon dioxide), methyl ethyl ketone (from the catalytic dehydrogenation of secondary butyl alcohol), phenol (from cumene peroxidation), phosgene (by reacting anhydrous chlorine gas and carbon monoxide), phthalic anhydride (by reacting xylene with oxygen), polyester fibers, polyester polyols (by condensation of a glycol and a carboxylic acid or acid derivative), polyethylene, polyglycols for urethanes, polyimides, propylene glycol (by hydration of propylene oxide at 200°C), propylene oxide (from chlorohydrin or peroxidation), pyridine and pyridine bases (by reacting acetaldehyde -usually with methanol or formaldehyde- with ammonia), sorbitol (by high-pressure catalytic hydrogenation of glucose in autoclaves), terephthalic acid and dimethyl terephthalate, urea, acrylic elastomers, acrylic resins (from catalytic oxidation of methyl methacrylate), amino resins (from the reaction of aldehydes and amino groups), aromatic ketone polymers (from condensation polymerization reactions), fluoropolymers (from tetrafluoroethylene reacting with acid, and surfactants), copolyester-ether elastomers, nylon resins, polyamide resins, polyacetal resins, polycarbonate resins, PBT resins (from bis-(4-hydroxybutyl)-terephthalate-BHBT), PET polymers (by polycondensation of ethylene glycol with either dimethylterephthalate or terephthalic acid), unsaturated polyester resins, and polystyrene resins (using free-radical polymerization of styrene with an initiator and heat)

Using Heat Capture for Delivery at Remote Locations

[0087] Embodiments of the invention include systems, methods, and apparatus for heating underground geological formations, such as oil deposits (e.g., enhanced oil recovery-EOR), without requiring water, CO₂, or steam injection. Preferred embodiments provide a broad spectrum of heat pipes that operate within the temperature range of 120 °C and 1,300 °C or higher, and that provide for fully automated heat recovery at temperatures similar to that range over several hours, days or months without user intervention. For example, systems disclosed herein can run without user control or intervention for 1, 2, 4, 6, 8, months, or longer. In preferred embodiments, the systems can run automatically for 1, 2, 3, 4, 5, 6, 7, 8 years, or more.

[0088] Figure 10 illustrates the use of a heat pipe for purposes of EOR. In Figure 10, the surface site (1) is assumed to have a drill hole (3) that was already in place or drilled specifically for the heat pipe, and a heat pipe (4) that reaches from the surface to the oil formation (2). During operation, heat is provided to the top of the heat pipe. The heat pipe efficiently transfers such heat directly from its top to its lower portion which is in contact with the oil strata. Since sedimentary oil formations can be located at substantial depth, the heat pipe (4) must be sufficiently long for it to reach into that formation. Therefore, an important problem to solve is how to design and manufacture such HP and how to insert a very long pipe into a vertical or inclined drill hole without excessively bending the pipe and thus damaging it.

[0089] Figure 11 describes one possible method for placing a long heat pipe into a drill hole. In Figure 11, a number of buoyant balloons (5) are used at suitable intervals along the length of the pipe (4) to neutralize its weight and thus prevent it from bending when lifting one of its ends. The actual lifting can be done with a helicopter (6) or similar airborne system (e.g., a drone). Once the heat pipe is aligned with the drill hole (3), its neutral weight makes it easy to lower it into position, gradually removing the individual lifting devices (5) from the pipe (4), until the pipe reaches the oil formation (2).

[0090] Figure 12 shows an alternative embodiment for placing a heat pipe down a drill hole. In Figure 11, the heat pipe 4 is wound around a circular wheel 25 with sufficient radius to minimize the curvature of the pipe and thus prevent damage to its internal mechanism. As the wheel is rotated, the heat pipe is then lowered into the drill hole 3.

[0091] Once in place, the heat pipe is ready for transferring heat from the surface to the oil formation directly without the need for pumps, external recirculation loops, or other mechanisms. Heat can be provided to the upper portion of the pipe on the surface by direct combustion of fuels (e.g., natural gas, oil), by solar heating through solar concentrators or parabolic troughs, electrical, geothermal sources, steam, waste heat at elevated temperatures, or any other type of energy source. Since heat pipes excel at axial heat transfer at rates that approach the speed of sound, the heat absorbed from surface sources rapidly reaches the oil formation where such heat is released.

[0092] An optional configuration entails using a heat pipe as described in the above paragraph together with steam injection. This allows the steam to maintain a high temperature throughout the length of the heat pipe, thus minimizing wall heat losses, while enhancing heat transfer and delivering higher temperature heat at the bottom of the heat pipe. In addition, steam condensation provides liquid water at the oil formation that enhances flow. This type of configuration can prove useful when there is a need for additional heat delivery or when the number of drill holes for EOR is limited.

Using Heat Capture for Delivery in Geothermal Fields

[0093] In other applications, such as the recovery of heat from geothermal fields, preferred embodiments include either heat pipes, thermosyphons, loop heat pipes, or pulsating heat pipes that operate within the temperature range of 250 °C and 1,300 °C and that provide for fully automated heat recovery at temperatures similar to that range over several hours, days or months without user intervention.

[0094] Figure 13 illustrates two embodiment options for extracting heat from a geothermal field. Geothermal sources typically derive heat energy from a deep magma chamber (27) (not drawn to scale in Figure 13), which heats a geothermal formation (26) that may have significant moisture or be substantially dry. Figure 13(a) assumes a wet geothermal formation, so that liquid water in the drill hole (3) can transfer heat directly to the heat pipe, pulsating heat pipe, or thermosyphon (4). As demonstrated in subsequent paragraphs, the heat pipe, thermosyphon, or pulsating heat pipe (4) provides a highly efficient mechanism for heat transfer from the geothermal formation (26) to the surface, where such heat can be recovered at

temperatures similar to those prevailing at depth and utilized directly without the need for either heat exchangers or water treatment.

[0095] Figure 13(b) illustrates an alternative embodiment for geothermal heat recovery when the geological formation is either very dense, or has low porosity or permeability, or lacks sufficient moisture to assist in heat conduction at depth. In those cases, the bottom of the drill hole (3) is enlarged at the bottom (28) in order to provide a greater surface area for thermal conductivity. To further increase thermal conductivity, this bottom portion of the hole can be partially filled with water (29) or other high thermal conductivity fluids. Furthermore, in order to preserve the high temperature in a geothermal field, it would be advantageous to cap the drill-hole at the top with a valve (30), so as to maintain the pressure and temperature prevailing at the geothermal depth, thus allowing the heat pipe, pulsating heat pipe, or thermosyphon (4) to transfer heat at the maximum possible temperature to the surface.

Description of Heat Transfer from an Industrial Source

[0096] Other embodiments capture heat from industrial plants and transfer it to sites that can use that heat at distances of tens to hundreds to thousands of feet. These systems can operate within the temperature range of 80 °C and 1,300 °C and provide for fully automated heat recovery at temperatures similar to that range over several hours, days or months without user intervention.

[0097] Figure 14 shows an embodiment for transferring heat in an industrial setting. In a typical industrial plant (31), a source of waste heat (32), which can include a power plant, a boiler house, an exothermic process vessel, or a chemical reactor that can be used to provide heat by means of heat pipes (4) which transfer such heat with minimal losses in temperature to remote places (33) which can include steam generation sites or other process vessels that require heat.

[0098] The chemical process industry covers many hundreds of chemicals and petrochemicals that either utilize highly exothermic processes, require temperatures of several hundreds of degree centigrade, or produce products that must be cooled or refrigerated rapidly. Examples include but are not limited to the manufacture of acetaldehyde, acetic acid, acetic anhydride, acetone, acetonitrile, acetylene, acrylamide, acrylic acid, acrylonitrile, adipic acid, alkyl amines, alkylbenzene, ammonia, aniline, ketone polymers, benzene, benzylchloride,

bisphenol A, butanediol, butylacetate, caprolactam, carbon disulfide, cellulose acetate, cellulose ethers, chlorinated isocyanurates, chlorinated solvents, chlorobenzenes, chlorinated methanes, cresols, xylenols, cumene, cyclohexane, dimethylformamide, epichlorohydrin, epoxy resins, ethanolamines, ethyl acetate, ethanol, ethyl benzene, ethylchloride, ethylene, ethylene dichloride, ethylene amines, ethylene glycol, ethylene oxide, fluorocarbons, formaldehyde, fumaric acid, furfural, glycol ethers, Hexamethylenediamine, hydrogen cyanide, hydroquinone, isophthalic acid, isopropyl alcohol, ketene, alkylsulfonates, alphaolefins, lignosulfonates, maleic anhydride, melamine, methanol, methylethyl ketone, methyl methacrylate, nitrobenzene, Nylon resins, phenol, phenolic resins, phosgene, phthalic anhydride, polyamide resins, polyacetal resins, polyalkylene glycols, polycarbonate resins, polyesters, polyethylene, polyglycols, polyimides, polypropylene, polystyrene, polyvinyl alcohols, propionic acid, propylene glycol, propylene oxide, pyridine, silicones, sorbitol, styrene, terephthalic acid, urea, vinyl acetate, vinyl chloride, and zeolites.

[0099] Another type of industrial application involves power plants, particularly those fueled by coal. These plants generate substantial volumes of combustion gases that require progressive treatment steps to reduce pollutants. Typically nitrogen oxides (NO_x) are generated during the combustion process and need to be reduced by adding ammonia or amines which reduce the NO_x to nitrogen gas. Next, the fly ash particles need to be captured and removed, which is normally done with electrostatic precipitators or baghouses, or both. The flue gases also contain significant sulfur compounds from the original coal, which is normally handled in a flue gas desulfurization (FGD) system involving scrubbing. In spite of these various treatment steps, the flue gas in a coal-fired power plant contains very large amounts of low-grade heat at temperatures in the range of 330 °F to 400 °F that can be tapped without unduly affecting the normal operation of the plant.

[00100] Other examples of heat capture, transfer, and release include:

In thermal power plants,

- The augmentation and replacement of cooling towers
- The augmentation and replacement of large condensers
- Extracting heat as steam and “hot furnace gas” to optimize cycle efficiency

- Recovering heat from the boiler house in small power plants
- In hot-pond power generation, using heat pipes to transfer heat
- Preheating pre-combustion gases
- Capturing heat from boiler blow-down

In nuclear power plants,

- Cooling of spent-fuel storage
- Cooling of reactor core
- Augmentation and replacement of steam condensers

In natural gas compression stations

- Recovering heat from large compressors

In underground mining

- Cooling deep working sites

In solution mining

- Heating underground formation to increase solubility

In plywood and OBS production

- Drying of raw materials

In the heat management of industrial processes, such as

- bio-fermentation
- fertilizer production (e.g., urea)

In industrial gas production

- Compressor heat in argon, nitrogen, oxygen, CO₂ production
- Gas liquification
- Coal gasification and syngas – Fischer-Tropsch process

In military applications, such as

- Stationary generators
- Mobile engines, such as vehicles
- Engines on ships
- Mobile/deployable heat pipe runway for both, cooling and heating

In solar applications

- Capturing, transferring, and releasing heat in solar concentrators
- Cooling of photovoltaic arrays

In metallurgical applications

- Crystal pulling (e.g., silicon) using radiant heat
- Continuous casting of steel and other metals using radiant heat and conduction
- Heat shielding by transferring heat away from the heat shield
- Cooling the molds in sand casting
- Cooling the laser head in laser cutting

Miscellaneous other applications, including heat sensitive industries in SIC code, such as

- Heat recovery from semi-conductor processing
- Rubber manufacturing, e.g., vulcanizing
- Oil refineries, including coker, distillation towers, and chemical reactors
- Augmenting and replacing HVAC systems for cooling and heating of residential and industrial buildings
- Freeze protection for agricultural applications, such as grapes and citrus.
- Decomposing undersea methane hydrate for gas production.

[00101] Since any type of heat pipe is exceedingly effective at heat transfer, the following section focuses on heat pipes, and how to improve their average performance so they can be applied not only to conventional applications, such as stabilizing Alaskan permafrost, but

also in a variety of industrial applications including but not limited to desalination, industrial transfer of heat, cooling, refrigeration, and the like.

About Heat Pipes

[00102] Clearly, heat pipes allow effective thermal transfer to be done. The heat pipes are driven by the temperature difference between their condensing and boiling ends (the ΔT) which is sufficient to maintain a very high heat flux through the heat pipe. Commercially available heat pipes transfer large amounts of heat (e.g., >200 W) and typically have ΔT s of the order of 8 °C (15 °F), or higher at higher power output, although some have ΔT s as low as 3 °C. The ΔT is not critical for EOR or geothermal applications because the difference in temperature between a surface heat source and the geological formation is several hundreds of degrees, but a low ΔT is generally desirable to optimize overall thermal efficiency. It is therefore useful to examine the thermal phenomena in a heat pipe. Insert working fluid here (92)

[00103] An important factor in maintaining a low ΔT is limiting the wall heat losses, which are a function of the surface area (and thus on the length) of the pipe and the thermal conductivity of the wall material and the media surrounding the HP. This need is not critical for normal HP pipes but is important for very long HP as claimed in this application. Figure 15 illustrates different possible embodiments of surface insulation for a long heat pipe so that most of the heat is transferred to the cool end and very little is lost along the walls of the HP in the middle section. In the embodiment illustrated in Figure 15(a), a good insulating coating (7) is used over most of the surface area, except for the areas where the heat pipe (4) either absorbs or releases heat. Adequate insulators for relatively low temperature (<150 °C) include the thermal insulator materials such as those used in steam pipes. Adequate insulators for high temperature operation can include various insulating bodies with ceramic compositions, such as zirconia, alumina, magnesia, and similar compositions. An optional configuration for superior insulation is shown in Figure 15(a) and entails a ceramic material containing close pores. Figure 15(b) shows another embodiment which consists of a tube enclosure (7) under partial vacuum. This enclosure provides superior thermal insulation, plus the advantage of an external vacuum that neutralizes the structural strain of the internal vacuum of the heat pipe. The type of enclosure tube can be similar to those utilized in the heat collector tube of parabolic solar concentrators. Figure 15(b) illustrates an embodiment that includes a structural support sleeve (24) that surrounds the heat

pipe (4) at regular intervals to prevent the weight of the heat pipe from overcoming the structural resistance of the heat pipe assembly, particularly for high temperature operations. Such structural support can serve the dual purpose of assisting in neutralizing the weight of the heat pipe both during its insertion into its final location and during operation.

[00104] Figure 15(c) illustrates another embodiment for extending the length of heat pipes with minimal loss of heat transfer performance. In Figure 15(c) the heat pipe (4) ends with a smaller diameter tube (40) that fits into a hollow semi-cylinder which is the end of another heat pipe. The surface area of the two heat pipes allows heat to transfer from one heat pipe to another, and thermal losses are minimized by a flexible insulating blanket (not shown). Figure 15(d) illustrates an alternative configuration for connecting two or more heat pipes (4) into a longer heat pipe using small diameter or capillary size endings of each heat pipe (40). This type of configuration utilizes a common feature of heat pipes, namely that the internal shape of a heat pipe has little influence on the heat transfer performance and functionality of the heat pipe. Both types of configuration lead to “articulated” heat pipes that are designed to pivot and bend at the junction of two or more heat pipes, thus allowing very long heat pipes to follow a non-straight path.

[00105] Figure 16 illustrates a typical commercial heat pipe (4), which ordinarily consists of a partially evacuated and sealed tube (10) containing a small amount of a working fluid (11) which is typically water, but which may also be an alcohol or other volatile liquid. When heat in the form of enthalpy is applied to the lower end of the heat pipe, the heat first crosses the metal barrier (10) and the internal wick (12) and then is used to provide the heat of vaporization to the working fluid (11) which permeates the entire surface of the wick. As the working fluid evaporates, the resulting gas (steam in the case of water) fills the evacuated tube and reaches the upper end of the heat pipe where the ΔT between the inside and the outside of the heat pipe causes condensation and, thus the release of the heat of condensation to the outside of the heat pipe. To facilitate continuous operation, the inside of tube (10) normally includes a wick (12) which can be any porous and hydrophilic layer that transfers the condensed phase of the working fluid back to the hot end of the tube.

[00106] An improvement in the ability to capture heat is the use of metal oxides and/or pigments that are dark or black and that absorb heat more readily, particularly in the case of radiation heat. One advantage of a heat pipe having a black exterior coating is that such black surface also excels in radiating heat at the cold end of the heat pipe.

[00107] Experimentally, the largest barriers to heat transfer in a heat pipe include: first the layer immediately adjacent to the outside of the heat pipe (the boundary layer), second the conduction barrier presented by the material of the heat pipe, and third, the limitation of the wick material to return working fluid to the hot end of the heat pipe. However, in EOR applications, the boundary layer adjacent to the exterior of the heat pipe is minimal for two reasons: first, because if direct heating is used or steam or pressurized hot water are not used, the thermal barrier becomes far less significant, and second because, on the oil formation side, any water tends to be quite saline which can readily collapse the molecular double layer responsible for most of the barrier. Figure 17 illustrates a high-performance heat pipe that minimizes these barriers. Note that the axial wick reduces the thermal barrier normally present in a conventional wick that is adjacent to the wall of the heat pipe.

[00108] In Figure 17, the heat pipe (4) is shown in a vertical position with the heat input at the top and heat release at the bottom. The heat transfer barrier that is adjacent to the exterior of the heat pipe can be minimized as described in the above paragraph. The heat conduction barrier through the metal casing of the pipe can also be minimized by using a very thin metal foil (10) instead of the solid metal tube of most heat pipes. Mechanical support for the metal foil must be sufficient to sustain moderate vacuum and is provided by a metal screen (13) that provides additional functionality by increasing the internal surface area available for providing the necessary heat of condensation/evaporation. An internal wick (12) is also provided to assist in the evaporation of the internal fluid by its large surface area and open porosity. Also, given the long distance that the condensed working fluid must travel inside the pipe, there is an additional axial wick structure (14) at least partially not attached to the walls that transfers fluid through capillary action, but independently from the surface wick action.

[00109] During operation, heat enters near the top and traverses the thin metal foil (10). The thinness of the metal foil facilitates heat transfer because thermal conductivity is an inverse function of the thickness of the material through which heat must travel. Upon reaching

the internal wick (12), heat rapidly evaporates the working fluid that is present in the wick. The saturated vapor travels rapidly through the internal volume of the heat pipe and reaches the opposite end of the pipe where the slightly lower temperature causes the condensation of the vapor back into the working fluid. In the process, the heat of vaporization has been transferred from the top of the heat pipe to the bottom. The condensed working fluid then flows by capillary action toward the hot end of the pipe through both the surface wick (12) and the central axial wick (14), thus providing the necessary volume of flow for maintaining a large heat transfer.

[00110] Figure 18 shows a graphical comparison of two heat pipes: one a conventional and one a novel design. In the conventional heat pipe, the main problem is maintaining a wick structure (12) uninterrupted over the entire length of the pipe. Ordinarily, this is not a problem with pipes a few feet in length or shorter. It becomes a serious difficulty when the length exceeds such dimensions. The novel design obviates this problem by having an axial capillary wick (14) that does not require sintering or high thermal conductivity, but that may consist of any porous material that is wettable by the internal working fluid. In either case, the objective is to be able to transfer heat energy efficiently from the heat source at the top of the heat pipe to the application area at the bottom of the heat pipe. That objective is difficult if not impossible to achieve with a conventional heat pipe, unless the internal wick can function without interruption. Another problem/limitation of HP is manufacturing very long tubes. Making long tubes is normally accomplished by either welding shorter tube lengths, or threading them, but in either case, the problem of leakage arises, especially when conventional pipes are partially evacuated before final assembly.

[00111] Internal wick materials include sintered copper spheres, metal grooves, metal screens, and other materials that contain a well-defined porosity.

[00112] Figure 19 illustrates an alternative embodiment that obviates the need for extremely long heat pipes. In the cross sectional view of Figure 19, shorter heat pipes (4) are assembled with intermediate reservoirs (8) that contain a thermally conductive fluid (9), which transfers heat from one heat pipe to another, thus lengthening the distance over which heat transfer occurs. However, this embodiment requires that the intermediate reservoir be hermetically sealed to prevent loss of heat transfer fluid (9). In addition, thermal losses will necessarily increase with this type of embodiment because of the increase ΔT at each junction,

and the higher thermal wall losses due to the surface area of the intermediate reservoir and its temperature. Yet, the proposed embodiment offers a practical solution to heat transfer over very long distance, especially in EOR applications since pipe joining is a common activity and high-temperature heat is normally available. The type of transfer fluid can be any heat conducting liquid that is chemically stable at the temperatures involved in the heat transfer junction, such as DowTerm®, certain eutectic salt mixtures, and the like. Those familiar with the art will also recognize that similar embodiments involving the joining of short heat pipes into longer ones while maintaining hermetic seals are also possible and therefore the proposed embodiment is merely exemplary and is not intended as a limitation on the scope of the invention.

[00113] The composition of the working fluid inside a heat pipe generally determines the temperature range of the heat pipe or thermosyphon. Low temperatures involve organic compounds such as ammonia, alcohols, ketones, aldehydes, or aromatic hydrocarbons that boil at temperatures lower than ordinary water or aqueous solutions. For high-temperature ranges, certain metals like sodium, potassium, magnesium, aluminum, lead, zinc, and their alloys provide working fluids that can work at temperatures in excess of 1300 °C. Another option is to use salts and mixtures of salt that sublime as a working fluid for both, high and low temperature heat pipes. Also included are metal oxides, borates having different hydration levels.

[00114] Figure 20 illustrates a method for making heat pipes of any length, and one that is especially suitable for the manufacture of very long heat pipes. The method begins with a tubular scaffold (**13**) made of a metal screen with wires that are strong enough and openings that are small enough to maintain structural integrity of the finished heat pipe once it is sealed under partial vacuum. Normally, mesh sizes of the metal screen in the range of 24 to 150 mesh could be suitable to maintain partial vacuums of the order of 0.1 bar. If higher vacuum is desirable, the size of the metal screen can be down to 325-400 mesh, and one can provide a double screen surface with larger screen holes on the inside surface of the tubular scaffold that will add rigidity to the external screen surface. Those familiar with the art will realize that there are different ways to manufacture such tubular scaffold: it can be pre-formed which limits the overall length to several hundred feet, or it can be woven in situ for longer distances.

[00115] Once the tubular scaffold is formed, it is inserted into a furnace (**19**) that can sinter or weld the finished surface of the heat pipe which is allowed to rotate, as shown in the

diagram of Figure 20. Next, a metal strip (17) made of thin metal foil that includes a slightly thinner strip of sintered wick material (18) on one side is continuously wound over the tubular scaffold, so as to form a tube. The winding angle of the metallic strip (17) will be determined by the width of the strip (17), and the degree of strip overlapping required to completely seal the winding surfaces together. The furnace (19) is essentially the next to the last step in forming a tube with an inner wick layer. Once the tube is complete, an axial wick can be placed, the working fluid inserted, and the pipe can be evacuated and sealed. Alternatively, the axial wick and the tube can be manufacture simultaneously.

[00116] Figure 21 provides cross sectional views of two embodiments for winding a long distance tube with an inner wick surface. In Figure 20(a) the wick (18) consists of strip of sintered spheres (17), and shows two upper strips of a porous flexible weave (20) that protrude over the edge of the wick. When wound around the tubular scaffold the weaves make contact with adjacent weaves, thus providing a continuous porous layer that constitutes a continuous capillary surface. This prevents the inner wick material from being isolated in any section of its axial length. An alternative embodiment is described in Figure 21(b), where the inner strip of wick material is placed at a slight angle with respect to the vertical line, so as to be wider than the thin metal foil being wound, so as to ensure proper contact of the inner wick material. Of course, this can cause a slight separation between the thin metal foils during winding, which can be sealed with a thinner strip of foil (21) that is wound around the pipe just before it enters the welding furnace, as illustrated in Figure 22.

[00117] Figure 23 illustrates an embodiment of the axial wick (12) that may consist of a single cylindrical porous body, a coaxial cylinder with an inner metal wire to provide rigidity, a coaxial cylinder where the capillary action derives from small beads made of glass, ceramic, or metal, or combinations thereof. To prevent bending of the axial wick and maintain its separation from the inner walls of the heat pipe (4), a series of radially spaced supports (22) is placed along the length of the wick prior to its insertion into the heat pipe. Such supports are generally thin sections that do not unduly reduce the free inner volume of the heat pipe, and thus do not reduce the mass flow of vapor along the length of the heat pipe.

[00118] An alternative method for manufacturing a suitable wick is by using a copper or other metal precursor. A metal precursor is a chemical substance that upon heating

decomposes into a metal. In the case of sintered copper wicks, the precursor can be copper beta diketone (CBDK) or copper acetylacetonate (CAA), both of which decompose into micron-sized copper particles upon heating in a reducing atmosphere. In general any organic precursor that can be decomposed, or any ionic precursor that can be electrodeposited can be candidates. A suitable wick can be made by slurrying micron-sized copper particles in CBDK or CAA and spreading the slurry into the inside surface of a copper tube or copper strip. The excess liquid is drained away, so the solid metal particles are subsequently held by surface tension of the funicular rings that form in the contact points of the metal particles. Upon heating in a reducing atmosphere, the CBDK or the CAA decomposes into copper that welds into the contact points of the metal particles, thus cementing them in place. Alternatively, providing a suitable electro-potential, Cu ions can be deposited to provide the desired glue. Numerous metal precursors are available for decomposition into different metals, and normal thermal diffusion will allow such precursors to cement similar and dissimilar metals, as long as the metallic particles and the precursor metal have some solubility with each other. For example, deposition of CU on Cu or Sn on Cu can both provide the good thermal contact via Cu or CuSn alloys bridges.

[00119] Following the installation of the axial wick, which is optional but desirable in a long heat pipe, the working fluid is inserted so it can saturate the inner surface of the wick and the volume of the axial wick. The volume of working fluid can be 0% to 25% higher than required for wick saturation, and in cases where the evaporated working fluid can become superheated in its vapor form, the excess working fluid can exceed 25%.

[00120] A potential problem may arise with the wick structure in very long vertical heat pipes because of the need to maintain capillary action against the forces of gravity. The height of a capillary rise, h , is defined by:

$$h = \frac{2\gamma \cos \theta}{\rho g r},$$

where γ is the liquid-air surface tension (force/unit length), θ is the contact angle, ρ is the density of liquid (mass/volume), g is local acceleration due to gravity (length/square of time[26]), and r is radius of tube.

For a water-filled glass tube in air at standard laboratory conditions, $\gamma = 0.0728$ N/m at 20 °C, $\theta = 0^\circ$ ($\cos(0) = 1$), ρ is 1000 kg/m³, and $g = 9.81$ m/s². For these values, the height of the water column is

$$h \approx \frac{1.48 \times 10^{-5}}{r} \text{ m.}$$

[00121] Thus for $r=0.0002$ m (0.2 mm), $h= 0.074$ m, and for $r= 0.000002$ m (2 micron), $h= 7.4$ m, and for $r= 0.000000002$ m (2 nm), $h = 7,400$ m. However, in actual industrial practice laboratory conditions do not necessarily apply: the value of surface tension normally decreases with temperature and the contact angle is rarely 0° , although by keeping the wick surface clean and using working fluids that are aqueous such values can be approached. The largest factor in maintaining capillary action, however, remains the radius of the capillary. Therefore, the wick pore size in very long heat pipes needs to be in the range of several nanometers and not in the micron range as it is normal for conventional HP. However, this is not a problem encountered with pulsating heat pipes or thermosyphons that do not have wick structures. The practical implication in terms of manufacturability suggests sintered wicks made of nano-particles or the use of nanotubes or nano-sized structured powders or films of similar size.

[00122] The final stages in making a heat pipe involve evacuating it by applying vacuum, and sealing it by crimping or welding. Figure 24 illustrates an alternative embodiment to the sealing operation, and consists of installing a valve **(23)**, that allows periodic checking of vacuum conditions during operation.

[00123] Figure 25 illustrates an alternative embodiment for making advanced heat pipes, those that due to thin walls and special wick structures exhibit superior thermal transfer performance, and are easy and inexpensive to manufacture. In Figure 25(a), the manufacturing process begins with two thin foils **(35)** that are first coated with wick material **(18)**. Because the wick is formed on a planar surface before the heat pipe is made, the wick structure can include different size materials. For example, next to the foil surface, the wick material can consist of nano particles in the range of a few nanometers up to 100 nanometers, depending on the ultimate vertical length of the heat pipe. In the case of common metals, such as copper and its alloys, this

initial layer of nanoparticles is then sintered at temperatures lower than for conventional HP, of the order of 500-700 °C. In our case it could be several hundred degrees lower. Alternatively, the initial layer of nanoparticles can be held in place by an adhesive that can be subsequently pyrolyzed and/or graphitized at temperatures of the order of 800-850 °C. Also they can be supported by a material that maintains its structure at the temperatures and vapor pressures used. For example, it could be 20 nm porous zirconia nanosponges decorated with nanofilms or nanoislands of Cu or Ni if water is the working fluid. Next, a second layer of wick material, such as particles in the range of 1 to 100 microns, can be deposited on the foil surface and the process of sintering or pyrolysis can be repeated, thereby increasing the amount of mutual attachment. Alternatively, a second layer of wick material can consist of copper gauze, which provides a superior pore structure for the wick. That gauze material can then be joined with the lower layer of wick material. Thus, the wick can be built up sequentially to contain different layers of different porosity and permeability. Thus, this type of heat pipe can have lengths up to 10-14 km.

[00124] Once the wick material has been formed onto the foil, a number of metallic scaffolds (13) can be placed between the two thin foils (35), so as to form separate cylindrical surfaces separated by flat foil surfaces, as illustrated in Figure 25(b). The foil surfaces that separate the individual scaffolds should then be sealed by soldering or crimping, or both. In Figure 25(b) one end of these cylindrical shapes is closed and sealed by crimping or soldering, or both. Partial vacuum is then applied to ensure good contact between the scaffolding material and the foil containing the wick layer(s). Ordinarily, such vacuum is sufficient to provide good contact between the foil and the scaffold, but subsequent sintering can effectively weld these surfaces together. The resulting cylindrical shapes thus become heat pipes (4) connected by thin metal foils (35). These can be used as such in applications that require large surface areas and effective heat transfer coefficients.

[00125] Figure 25(c) illustrates the option of separating the connected heat pipe assembly into individual heat pipes, each having a couple of thin metal flaps for added surface area. However, such foil surfaces can be trimmed or cut away, as shown in Figures 25(d), to ultimately make individual heat pipes, as shown in Figure 25(e).

[00126] Figure 26 illustrates an optional configuration for transferring large amounts of heat over long distances, particularly at depth or in vertical arrangements. In Figure 26, the

heat pipe (4) consists of a “pulsed” heat pipe (*See*, “An Introduction to Pulsating Heat Pipes.” Electronics Cooling Magazine. [www <dot> electronics-cooling <dot> com/2003/05/](http://www.electronics-cooling.com/2003/05/), which is incorporated herein by reference in its entirety). In figure 26, heat is delivered at one end of the heat pipe (4) by any source of heat energy. The heat pipe (4) is partially filled with a liquid fluid (45) that evaporates as vapor (46) when heat is absorbed by the heat pipe. The vapor (46) increases the internal pressure of the heat pipe and causes both vapor (e.g., steam bubbles) and liquid plugs (e.g., slugs) to move in one direction, because a one-directional valve (47) prevents flow in the other direction. The internal flow of vapor and liquid transports heat by mass transfer to the other extreme of the heat pipe assembly which is at a lower temperature. This heat transfer causes heat to be released by condensation of vapor to liquid (the release of the latent/sensible heat contained in the liquid phase). As heat is transferred, additional vapor is condensed into liquid phase and that liquid continues to flow in response to the pressure pulses.

[00127] What distinguishes the present invention from conventional pulsating heat pipes is that the heat pipe can be manufactured according to the principles noted in the previous discussion regarding long-distance heat pipes in Figures 20 through 22, except that the reinforcing screens (13) would be placed external to the metal foil (17), so as to provide strength to resist the internal pressure pulses, and the lack of a need for an internal wick material (18). Alternatively, pulsating heat pipes can be assembled using conventional methods of joining pipes. Additional distinguishing features include the use of specialty coatings on the inner surface of the heat pipe to promote evaporation and boiling, and/or on the outside of the heat pipe to enhance heat transfer to a geologic formation or other heat requiring application. In addition, the external surface of the pulsed heat pipe can be thermally insulated, except at the ends. Thus, this type of heat pipe can have lengths up to 10-14 km.

[00128] Effective heat transfer that occurs without significant temperature loss is also attractive for thermal power plants that have substantial volumes of waste heat available, but at temperatures that are normally too low for various industrial applications. However, a novel technology has been developed by Sylvan Source, Inc, (US Patent No. 8,771,477, and patent application No PCT/US2012/054221, with international filing date of 7 September of 2012, and priority date of 9 September of 2011, incorporated herein by reference in its entirety) that can

purify a broad range of contaminated waters using very little heat energy, and that technology can be combined with heat capture to provide useful heat capture with water purification.

[00129] However, for such innovation to be effective the capture of heat, its transport to where it can be used, and its subsequent delivery must take effect with a minimum of temperature losses. Heat pipes, thermosyphons, and pulsating heat pipes provide a practical solution, provided that the heat pipe system can fulfill all three functions simultaneously and without intermediate steps. Thus, there is a need for long-distance heat pipes that can capture low-grade as well as higher temperature heat, transfer such heat energy to a larger diameter heat pipe with no temperature loss, and deliver such heat energy to a number of smaller diameter heat pipes for actual utilization, again not suffering significant temperature loss. One way in which this can be accomplished is by having a number of smaller diameter heat pipes **(4)** seamlessly connected to a larger diameter heat pipe **(58)**, and in turn connected to a heat delivery system consisting of smaller diameter heat pipes **(4)**, as illustrated in Figure 1.

[00130] Clearly, for a complex heat pipe to function as a single unit it is essential that the mechanism for returning the working fluid to the hot end of the heat pipe must not be interrupted. That means that the internal wick that functions by capillary action must be interconnected throughout the various joints between the heat pipe elements. Since joining metallic heat pipes would normally be accomplished by welding the external encapsulating material and such welding cannot be used to join the sintered wick, the question becomes “how to provide for capillary continuity” when joining dissimilar heat pipes. Figure 27 illustrates a method to accomplish this purpose.

[00131] Figure 27(a) shows how to join two heat pipes **(4)** and **(58)** of different diameter. A hole is cut into the larger heat pipe **(58)** so that the smaller heat pipe **(4)** can fit precisely. A doughnut-shaped gel **(48)** containing particles of the same size as the wick material is placed at the end of the smaller heat pipe **(4)**, as shown in Figure 27(b), and the two heat pipes are joined as shown in Figure 27(c). Figure 27(d) shows an enlarged cross-sectional view of the two heat pipes and the gaps that exist in the wick material. Figure 27(e) illustrates what happens when solder **(49)** or a weld is applied to the external surfaces of the two joined heat pipes: the gel material liquefies and evaporates, but not completely, thus allowing capillary action to draw in the suspension of microscopic particles so as to fill the gaps in capillary material **(12)**. The heat

of soldering or welding is sufficient to evaporate all of the liquid used to suspend the microscopic particles, leaving behind small funicular rings that can pyrolyze, thus holding the new wick particles together (50), as shown in Figure 27(f). Additional heat can then be applied, if needed, in order to sinter the additional wick particles together. And of course, all of the above requires that there is no vacuum at the time the heat pipes are being joined. An example of a gel that could perform as indicated is a silica gel, which would leave welding spots between the new wick material consisting of silica--a hydrophilic substance that would facilitate capillary continuity. However, the silica would likely dissolve and move from the hot to the cold side of the heat pipe, so a preferred material would be a silica gel that has alumina particles, zirconia or rare earth particles in suspension, so they permanently weld the wick together.

[00132] Another important feature of an advanced heat pipe, particularly one that integrates several small diameter and large diameter heat pipes, is the ability to stop the transfer of heat at will, such as in industrial situations where the main plant must be disconnected from the heat transfer mechanism. Figure 28 illustrates one mechanism of controlling heat transfer in an advanced, complex heat pipe. As shown in Figure 28(a) a simple valve (60) that can be electronically or remotely controlled is attached to the inside of the large diameter heat pipe (58) and, while valve (60) is open, the heat pipe continues to transfer heat as designed. Figure 28(b) illustrates what happens if the valve closes in response to an external actuator: the flow of gaseous working fluid stops entering the small diameter heat pipe (4) and thus heat transfer is interrupted.

[00133] An optional configuration of advanced heat pipes includes hybrids of heat pipes with pulsating heat pipes and/ or loop heat pipes that combine the best features of each type of heat pipe into a single entity with superior performance. For example, a combination of a pulsating heat pipe can provide for optimum heat capture and release, while a standard or loop heat pipe that is an integral element provides for optimum heat transfer. Such a hybrid can include thin wall thickness at the heat capture and release ends, and thicker walls with or without thermal insulation to prevent long-distance losses, and a common wick material that ensures continuous fluid communication inside the hybrid pipe due to capillary action. Furthermore, the capillary wick can consist of an axial or spirally wound wick that periodically touches the internal wall, thus maintaining capillary continuity throughout the length of the heat pipe. Such

flexible wick can be used to join different heat pipes prior to welding, thus also maintaining capillary continuity. Alternatively, the wick material can be grooved for the long-distance section of the heat pipe, thus providing for different wick structures that optimize each function of the heat pipe: heat capture, transfer, and release. Another option involves the use of metallic screens that can weld onto slightly larger or smaller diameter screens that provide for capillarity.

Heat Release using heat pipes, spreader heat pipes, thermosyphons, and pulsating heat pipes

[00134] The release of heat involves the same principles as the capture of heat, except that in the case of heat pipes, particularly in conventional heat pipes, the execution of those principles are in the reverse order. Thus, releasing heat from a conventional heat pipe involves first the condensation of the internal vapor at the cold end of the heat pipe, then the transfer of that heat via thermal conductivity through the wick material and subsequently through the encapsulating tube which is normally a metal or alloy, and ultimately the dissipation of that heat to the medium outside the heat pipe. In the case of advanced heat pipes which may contain multiple wick layers of different porosities, the thermal conductivity will depend on the thickness of each wick layer and the thermal conductance of the wick material. In the case of pulsating heat pipes and thermosyphons, when there is no wick, the thermal conductivity through the encapsulating tube will depend on whether the internal fluid is in liquid or gaseous form, as well as the thermal conductance of the tube and its thickness.

[00135] The numerous possible configurations described in the previous paragraphs have distinct advantages for releasing heat efficiently, such as:

- The use of thinner wall thickness in the encapsulating material for heat pipes minimizes temperature loss while enhancing the amount of heat being transferred per unit of surface area, as illustrated in figures 17, 20, 22, and 25.
- The use of thin foils as illustrated in figure 25 allows the simultaneous manufacture of thin fin structures that enhance the surface area and maximize heat release.
- The ability to join multiple sections of a complex heat pipe while maintaining wick consistency and continuity, allows the capture of heat from different places, the transfer of such heat over short or long distances using a larger, more efficient heat

pipe, and the delivery of such heat to multiple places by means of smaller heat pipes.

- The control features of an on/off switch in heat pipes that allows one to interrupt or to maintain the flow of heat at will.
- The use of special configuration heat pipes, such as pulsating heat pipes, that permit the vertical or horizontal transfer of heat over very long distances.
- The use of different encapsulating materials for the ends and the middle of heat pipes that optimize heat capture and release, while minimizing heat losses during heat transfer by means of connecting materials having low thermal conductivity, or insulating coatings on the outside of the heat pipes.
- The possible integration of heat pipes with heat storage systems that provide for operational flexibility in industrial plants.

All of these contribute to superior thermal characteristics.

[00136] The ability of capturing, transferring, and releasing heat more efficiently than heat exchangers, or the so called “economizers” that rely of thermal fluids, or quenching operations based on water sprays confers distinct advantages to the heat pipes described in previous paragraphs in multiple industrial applications, such as:

- In water purification and, in particular, in desalination of seawater, purification of brackish water, purification of ultra-saline aqueous waste from oil and gas extraction, chemical or metallurgical processes, pulp and paper industries, and plastic and rubber operations, to name a few. In effect, the low temperature differential afforded by heat pipes permits the use of more effective multiple evaporators in distillation systems, and the superior heat transfer of heat pipes enhances thermal performance. Furthermore, water purification configurations can include multiple designs, such as vertically arranged stacks, laterally arranged distillation systems, or hybrid configurations that fall under the category of “distillation cores.”

- In chemical and petrochemical processing that require either effective cooling of exothermic reactions, maintaining of reaction temperatures within a narrow range, refrigerating of vessels for synthesis or catalytic reactions at low temperatures.
- In power plants, nuclear plants, and similar industries that require effective cooling, such as by the replacement of cooling towers and other cooling systems with highly effective heat pipe driven condenser vessels. Conversely, in using the heat release features of heat pipes for pre-heating process vessels, or controlling the temperature of flue gases. And particularly in the recovery of low-grade heat from flue gases using aero-dynamically shaped heat pipes that may also be inclined from orthogonal angles in order to reduce drag.
- In metallurgical operations that generate heat intermittently, such as steel and non-ferrous plants, or that require controlling temperature as in metallurgical digestion processes such as in the Bayer process.
- In the efficient transfer and release of large heat energies, as in enhanced oil recovery, oil and gas fracking operations, gas hub operations that recover heat from compressors, oil refineries (e.g., distillation towers, coker operation, and cooling towers), geothermal energy production, and metallurgical and chemical operations.
- In miscellaneous applications, such as food and beverage processing.
- And especially in military operations that generate large amounts of waste heat while requiring potable water obtained from contaminated sources.

[00137] One skilled in the art will appreciate that these methods and devices are and may be adapted to carry out the objects and obtain the ends and advantages mentioned, as well as various other advantages and benefits. The methods, procedures, and devices described herein are presently representative of preferred embodiments and are exemplary and are not intended as limitations on the scope of the invention. Changes therein and other uses will occur to those skilled in the art which are encompassed within the spirit of the invention and are defined by the scope of the disclosure. For example, an inner wick can be sprinkled inside the pipe tube and subsequently sintered at the appropriate temperature, which depends on the sintered material.

[00138] All patents and publications are herein incorporated by reference to the same extent as if each individual publication was specifically and individually indicated to be incorporated by reference.

[00139] The invention illustratively described herein suitably can be practiced in the abs of any element or elements, limitation or limitations which is/are not specifically disclosed herein. The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention that in the use of such terms and expressions indicates the exclusion of equivalents of the features shown and described or portions thereof. It is recognized that various modifications are possible within the scope of the invention disclosed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention as defined by the disclosure.

WHAT IS CLAIMED IS:

1. A heat management system comprising a plurality of heat transfer devices selected from the group consisting of conventional heat pipes, advanced heat pipes, thermosyphons, heat spreaders, pulsating or loop heat pipes, steam pipes, or combinations thereof assembled into an entity providing continuous thermal communication, adapted to capture, transfer, and release heat at temperatures in the range of -40 °C to 1,300 °C at a distances of from 0.1 m to 14 km, with a temperature loss from capture to release between 0% and 40% of a temperature at a source of the heat to be transferred, wherein the heat thus transferred is from one or more heat sources, and wherein the heat transfer devices capture or provide heat for at least one application.

2. A heat management system comprising one or more heat transfer devices selected from the group consisting of conventional heat pipes, advanced heat pipes, thermosyphons, heat spreaders, pulsating or loop heat pipes, or steam pipes assembled into an entity providing continuous thermal communication adapted to capture, transfer, and release heat at temperatures in the range of -40 °C to 1,300 °C at a distance of from 500 m to 14 km with a temperature loss from capture to release between 0% and 40% of a temperature at a source of the heat to be transferred, wherein the heat thus transported is from one or more heat sources, and wherein the heat transfer devices capture or provide heat for at least one application..

3. The system of claim 1, wherein the heat transfer devices have one or more wicks.

4. The system of claim 1, wherein the heat transfer devices have no wicks.

5. The system of claim 1, wherein the heat transfer devices comprise multiple sections, the sections being selected from evaporators, heat transfer sections, and condensers, or a combination thereof.

6. The system of claim 5, wherein the sections comprise a wick characteristic selected from no wicks, full wicks, partial wicks, and any combination thereof.

7. The system of claim 1, wherein the at least one application is selected from power plants, geothermal energy production, enhanced oil recovery, gas recompression, water desalination, metallurgical processing, chemical and petrochemical operations and production, pulp and paper industries, plastic and rubber operations, refractory industry, glassmaking operations, mining operations, plywood and oriented strand board manufacturing, fermentation, fertilizer production, industrial gas production, military applications, solar energy production, rubber manufacturing, and oil refineries.

8. The system of claim 1, wherein the heat transfer devices comprise an encapsulating material manufactured from the group of materials consisting of steel, copper and its alloys, titanium and its alloys, aluminum and its alloys, nickel and chromium alloys, wound metal foils, wire screens and scaffolds.

9. The system of claim 8, wherein the encapsulating material of the heat transfer devices includes a metal, plastic, or ceramic composition that is non-reactive with respect to the variety of heat sources, non-reactive with respect to a heat transfer medium, and non-reactive with respect to the heat source.

10. The system of claim 8, wherein the heat transfer device comprises different metals and alloys comprising varying thermal conductivities.

11. The system of claim 3, wherein different individual wicked heat transfer devices are joined such that a joined wick structure exists, having continuity compatible with capillary action along the length, the continuity permitting thermal communication of internal working materials throughout the length, and wherein the internal working materials are selected from the group consisting of fluids, solids that sublime, materials having multiple chemical hydration levels, and any combination thereof.

12. The system of claim 3, wherein the wick structure comprises multiple layers having different porosities.

13. The system of claim 3, wherein the wick structure comprises an internal wick structure comprising an axial wick.

14. The system of claim 3, wherein the wick structure comprises at least one material selected from the group consisting of sintered metals, metal screens, grooves, oxides, borates, solids that sublime, materials with different chemical hydration levels, nano-particles, nanopores, nanotubes, and any combination thereof.

15. The system of claim 14, wherein different materials are used at different positions along the length, and wherein the materials are selected to optimize heat capture and release, while minimizing heat loss.

16. The system of claim 3, wherein the wick is formed by spraying, painting, baking, PVD, CVD, or pyrolysis of organic compounds.

17. The system of claim 3, wherein the wick is formed by thermally decomposing a slurry of metal particles in a liquid metal precursor.

18. The system of claim 1, wherein the encapsulating tube comprises a wound strip of thin foil.

19. The system of claim 18, wherein the wound strip structure is pre-coated with wick material before being formed into tubular assemblies around metal scaffolds comprising mesh screens.

20. The system of claim 18, wherein gaps in the wound tube are sealed by a separate wound strip.

21. The system of claim 20, wherein the amount of working material is in excess of what is needed to saturate the internal wick structure.

22. The system of claim 1, wherein the working material in the heat transfer devices has phase change temperature in the range of -40 °C and 1,300 °C.

23. The system of claim 1, wherein the heat transfer device comprises a valve proximate to one end in order to control and maintain partial vacuum.

24. The system of claim 1 or claim 2, wherein vertical heat transfer devices of up to 14km in length are installed to prevent the physical degradation or breakage of the heat transfer devices, wherein the weight of the heat transfer device is neutralized by at least one buoyant balloon, at least one helicopter, or a combination thereof.

25. The system of claim 1 or claim 2, where the heat transfer devices are installed using at least one installation aid selected from a crane, a helicopter, a balloon, a wheel, an oil rig, and a tower, or any combination thereof.

26. The system of claim 2, wherein heat transfer devices of 3-7 Km in length are installed without physical degradation or breakage of such heat transfer devices, and wherein the heat transfer device is wound around a wheel of 100-500 feet in diameter that minimizes the curvature of the heat transfer device.

27. The system of claim 1 or claim 2, where the heat transfer devices are insulated.

28. The system of claim 1, wherein pulsating heat pipes are made by encapsulating a thin metal or alloy layer in a strong metal screen to resist pressure pulses.

29. A method of heat capture, transfer and release, using the system of claim 1.

30. A method for manufacturing the system of claim 1, comprising the steps of:
- selecting the type of heat transfer device from the group consisting of conventional heat pipes, advanced heat pipes, thermosyphons, spreader heatpipes, loop heat pipes, pulsating heat pipes, steam pipes and any combination thereof;
 - selecting a method of joining heat transfer device elements from at least one method the group consisting of soldering, brazing, welding, threading, foil winding, mechanical fittings, encapsulating thermal fluids, and any combination thereof;
 - selecting a type of wick structure from the group consisting of sintered metal, axial wick, metal screens, grooves, any combination thereof, and no wick material;
 - selecting the internal working material from the group consisting of aqueous solutions, eutectic salt mixtures, organic thermal fluids, and high-temperature metals and alloys that liquefy at temperatures in the range of -40 °C to 1,300 °C, solids that sublime, and materials with different chemical hydration levels;
 - applying the joining method, wick structure, and working fluid thus selected; and
 - sealing the heat transfer device under vacuum.