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(54) **ACTIVE MULTIPHASE HEAT TRANSPORTATION SYSTEM**

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(75) Inventor: **Satish Chandra Mohapatra,**  
Easton, PA (US)

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Correspondence Address:  
**Ashok Tankha**  
**36 Greenleigh Drive**  
**Sewell, NJ 08080 (US)**

(57) **ABSTRACT**

(73) Assignee: **Dynalene Inc.**

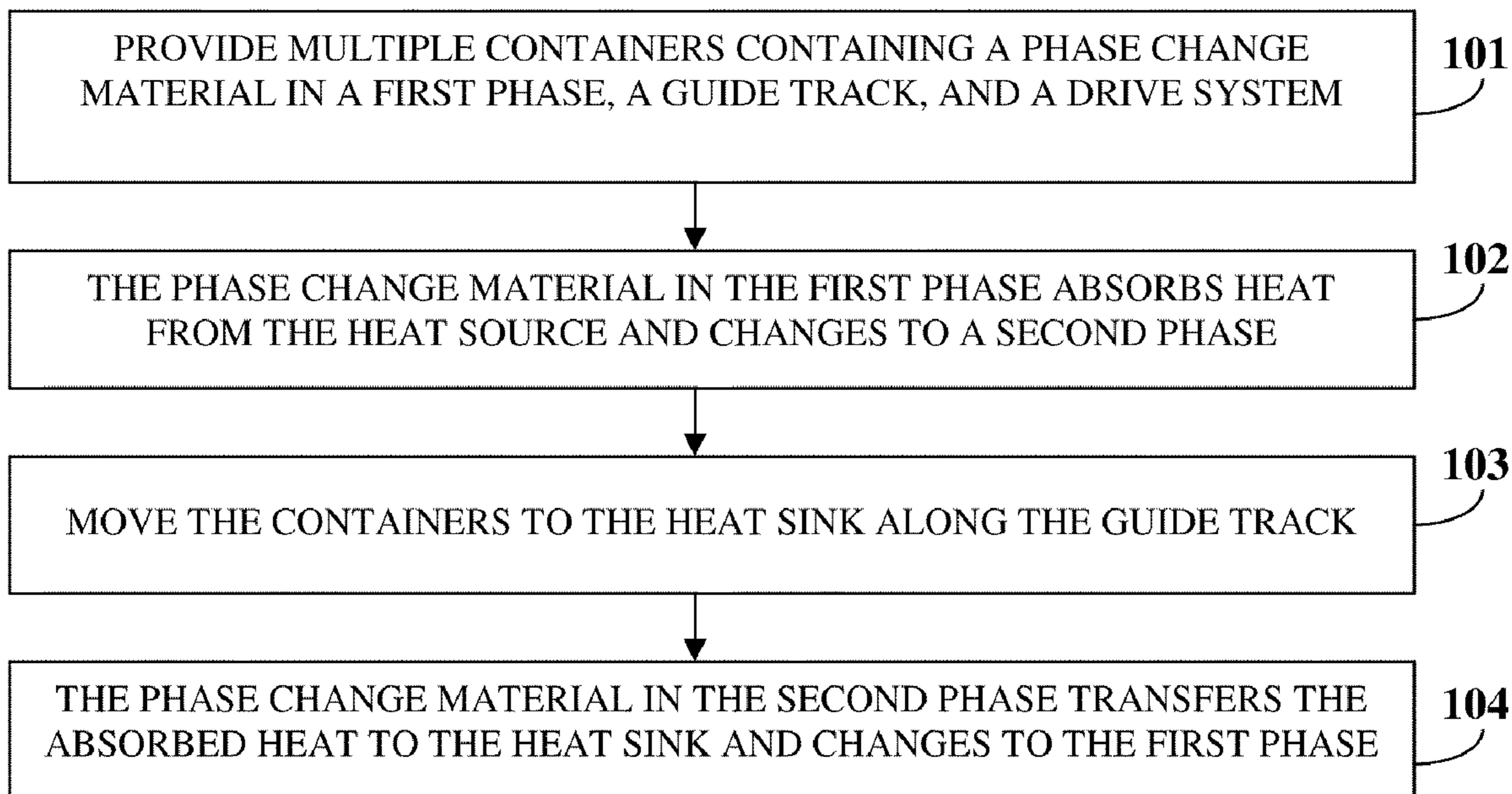
Disclosed herein is a method and system for transporting heat from a heat source to a heat sink. Containers containing a phase change material in a first phase, a guide track leading from the heat source to the heat sink, and a drive system are provided. The phase change material in the first phase in the containers absorbs the heat from the heat source on establishing thermal contact with the heat source and changes to a second phase. The drive system moves the containers containing the phase change material in the second phase to the heat sink along the guide track. The phase change material in the second phase in each of the containers transfers the absorbed heat to the heat sink and changes to the first phase. The heat source is cooled due to transportation of the heat from the heat source to the heat sink.

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**Related U.S. Application Data**

(60) Provisional application No. 61/060,140, filed on Jun. 10, 2008.



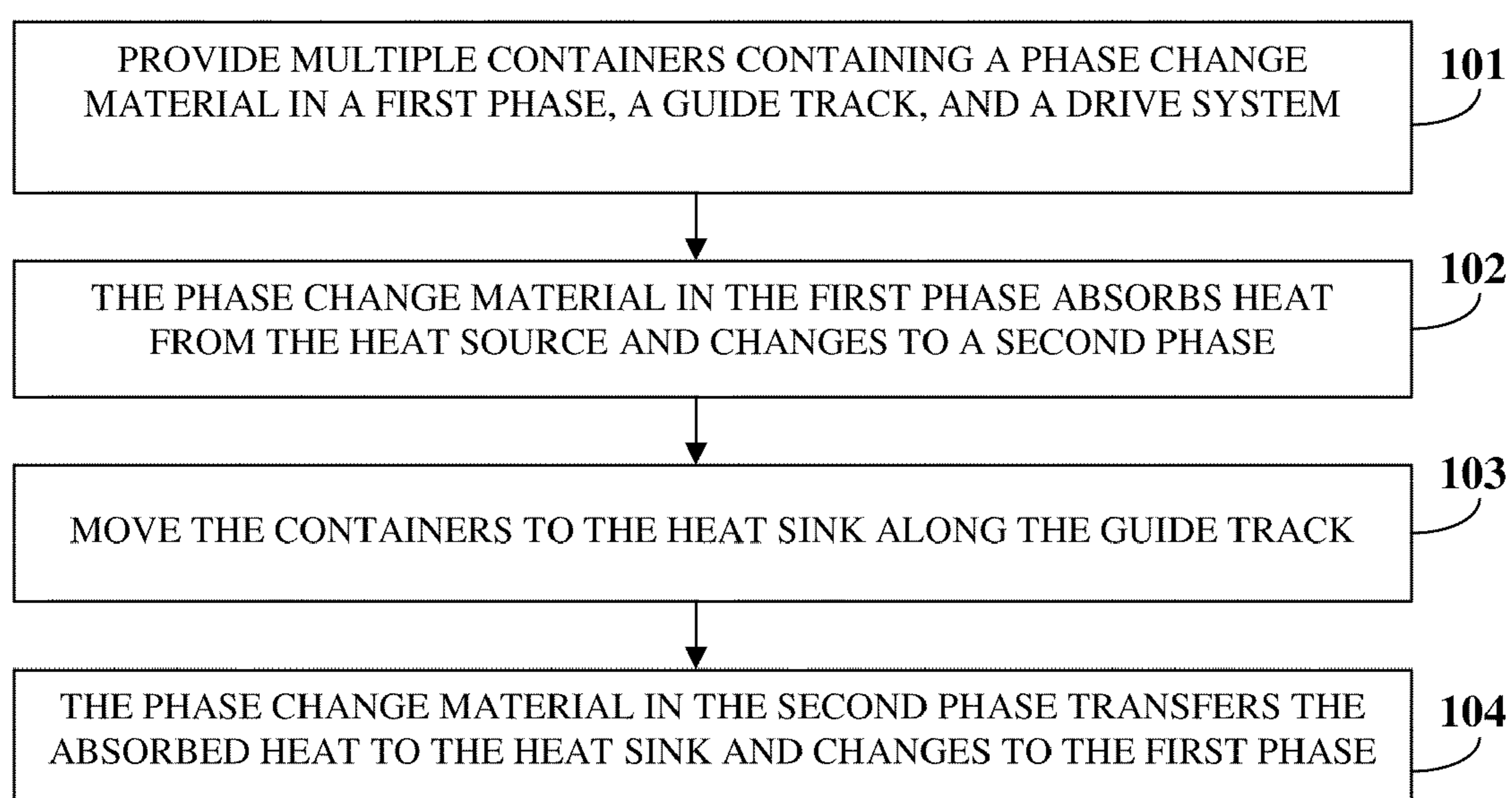


FIG. 1

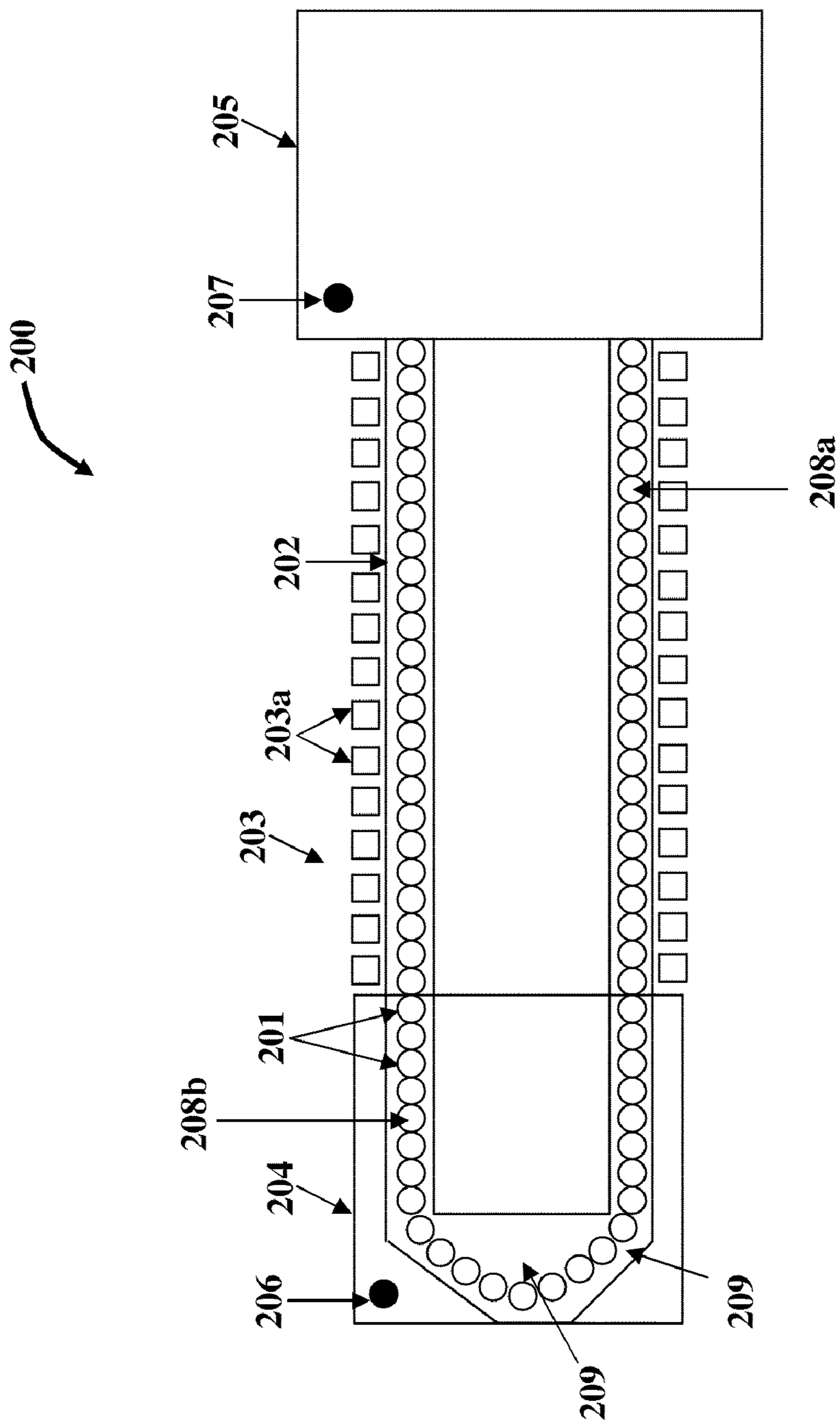


FIG. 2

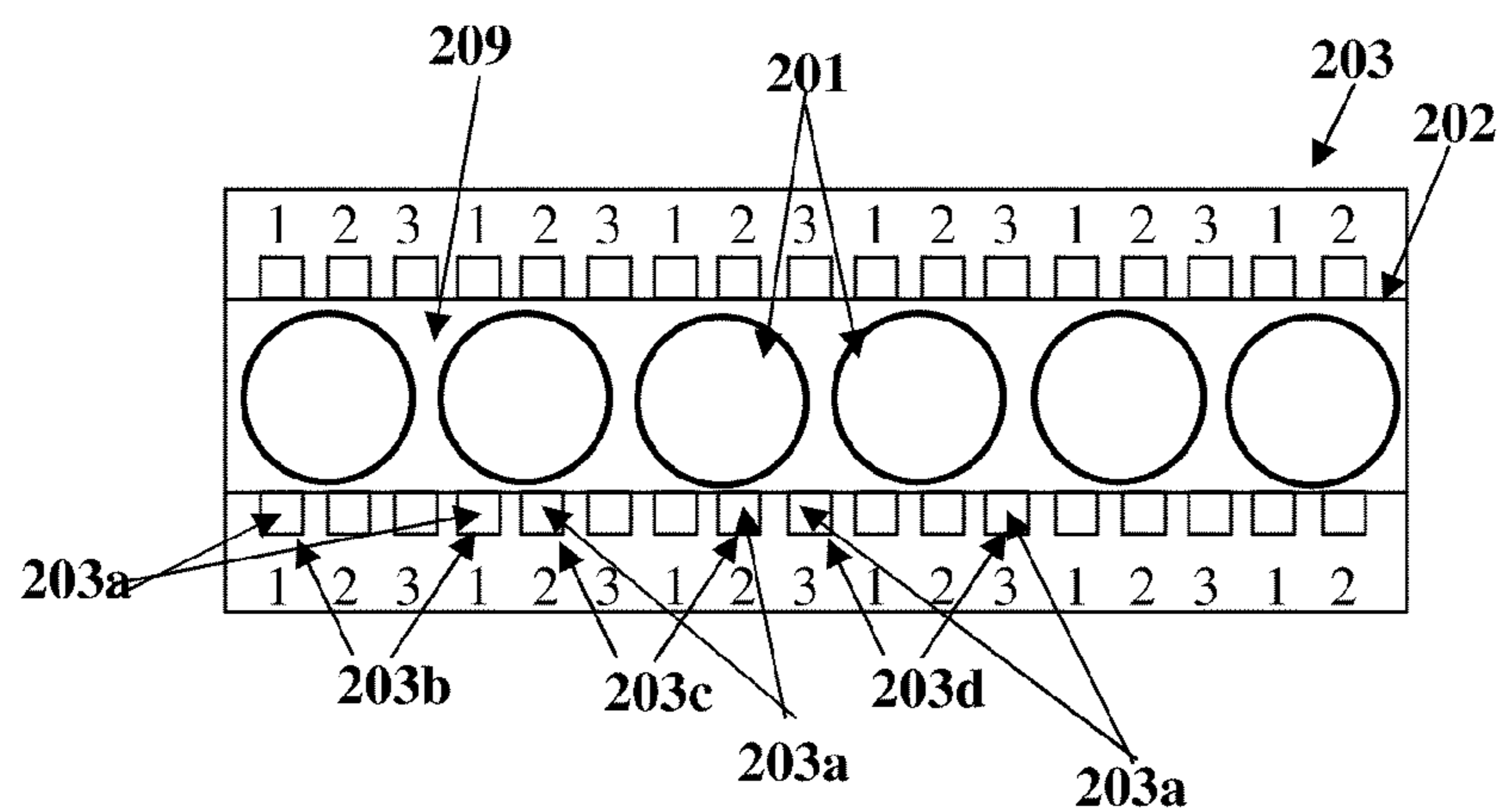


FIG. 3

Phase Change Material	T <sub>melting</sub> (°C)	Latent Heat of Fusion (kJ/kg)
Eicosane (C <sub>20</sub> H <sub>42</sub> )	36.4	217.62
Pentacosane (C <sub>25</sub> H <sub>52</sub> )	53.3	224.32
Tritriacontane (C <sub>33</sub> H <sub>68</sub> )	71.1	226
Camphene (C <sub>10</sub> H <sub>12</sub> )	51	238.55
(+)-Camphene (C <sub>10</sub> H <sub>12</sub> )	40-43	≈238
(-)-Camphene (C <sub>10</sub> H <sub>12</sub> )	36-38	≈238

FIG. 4

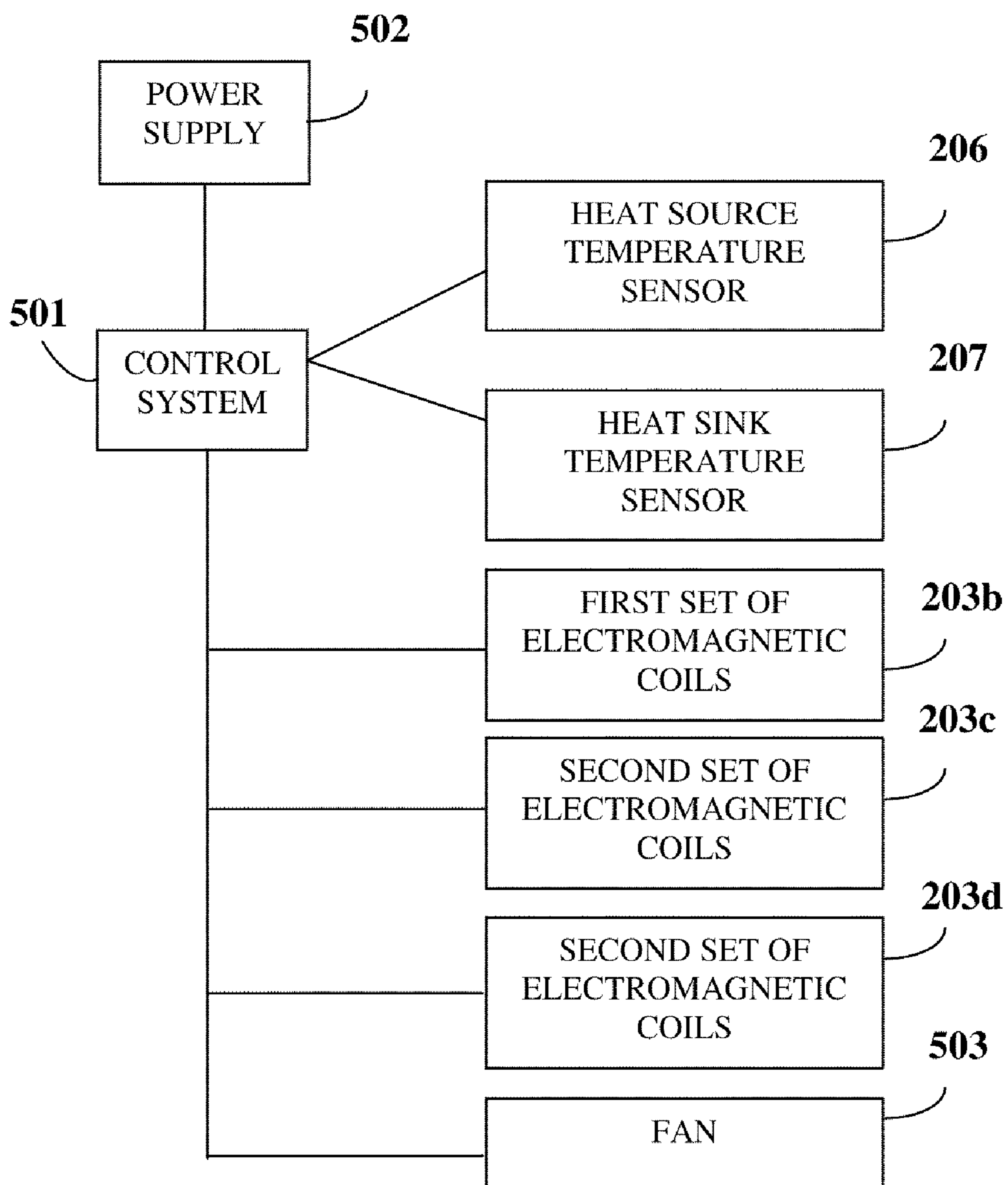


FIG. 5

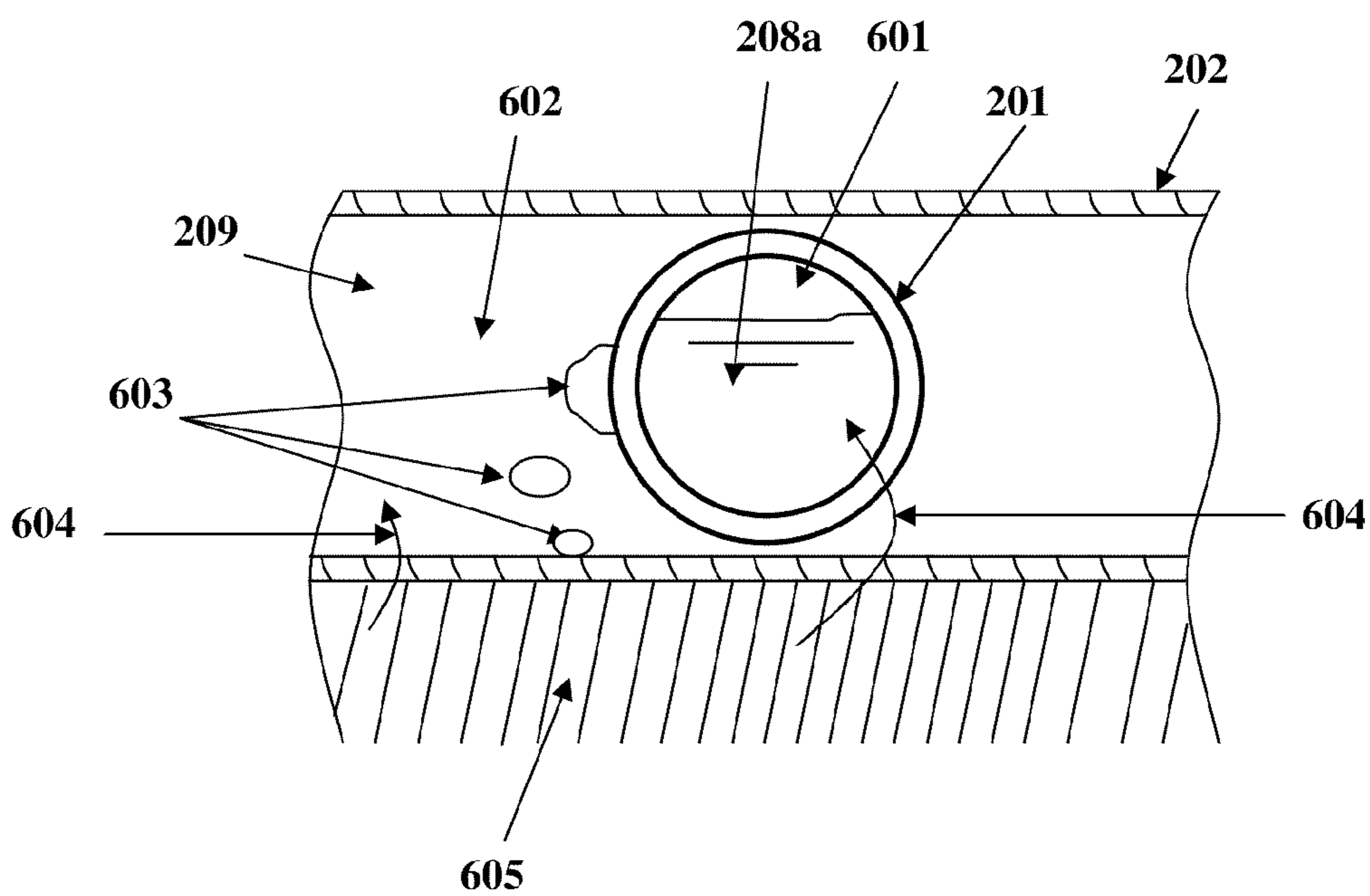


FIG. 6A

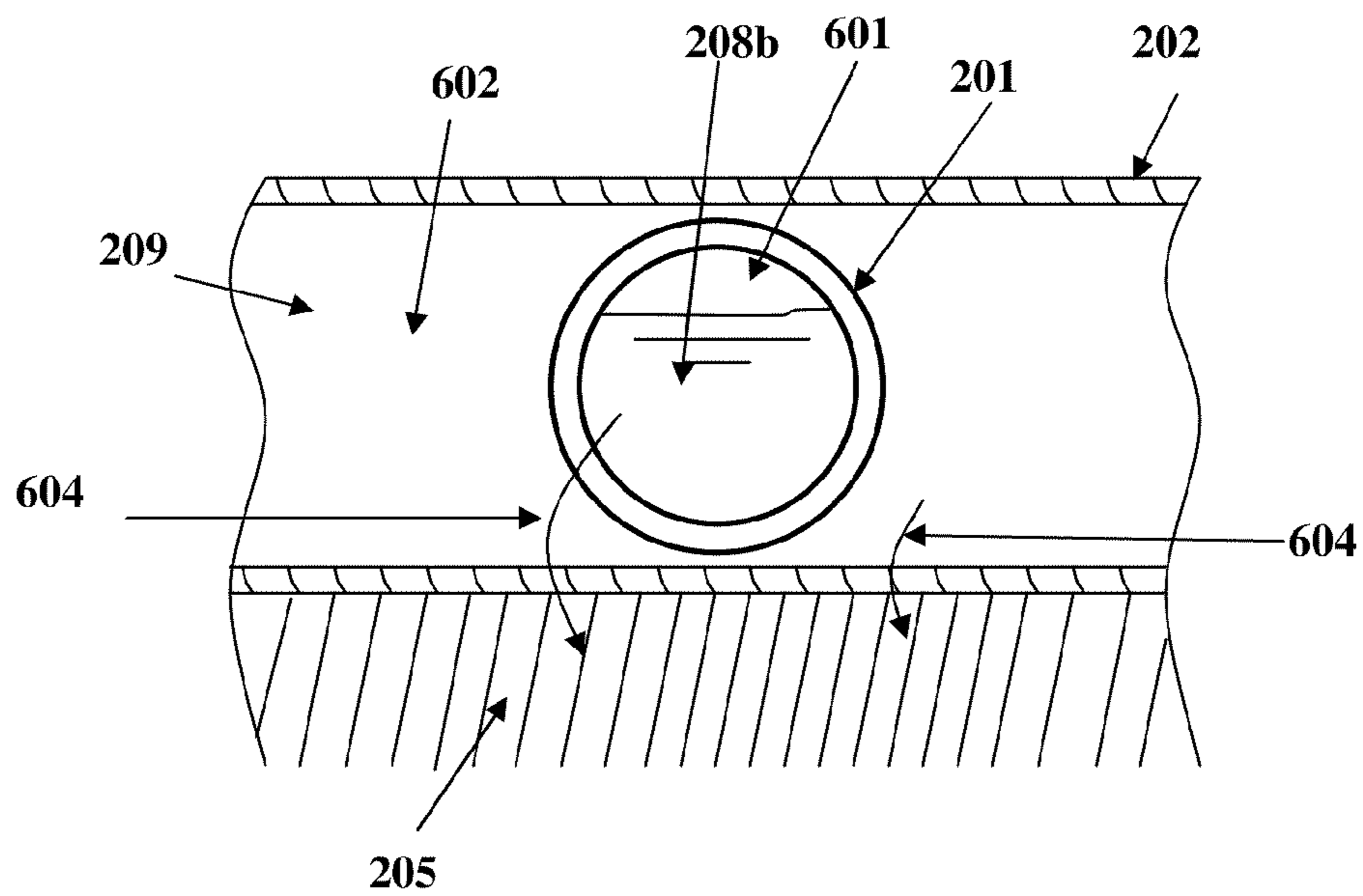


FIG. 6B

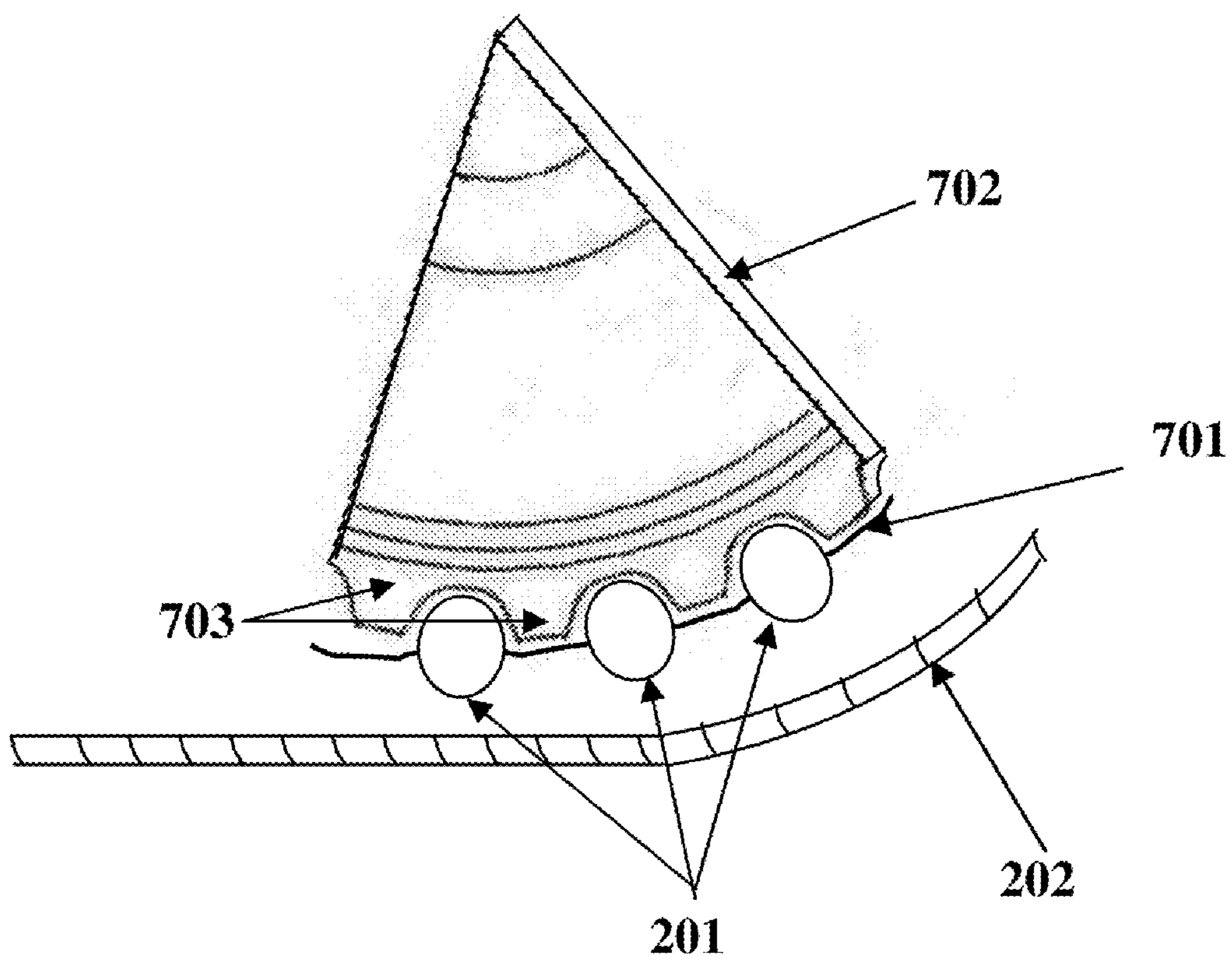


FIG. 7

## ACTIVE MULTIPHASE HEAT TRANSPORTATION SYSTEM

### CROSS REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of provisional patent application No. 61/060,140 titled "Freeze Tolerant Heat Transfer System", filed on Jun. 10, 2008 in the United States Patent and Trademark Office.

### BACKGROUND

**[0002]** The method and system disclosed herein, in general, relates to heat transfer systems. More particularly, the method and system disclosed herein relates to an active multiphase heat transportation system that transports heat from a heat source to a heat sink.

**[0003]** Cooling of microprocessors and other electronic components has become a major issue in recent times as faster and smaller components are being designed. As a result, different cooling technologies have been developed to effectively remove and transport heat from the electronic components for faster and stable operation. For example, for high power electronics, with a heat flux of 500 W/cm<sup>2</sup> to 2000 W/cm<sup>2</sup>, the need for advanced cooling technologies has significantly increased due to the failure of traditional heat transfer technologies.

**[0004]** There are two major problems associated with the removal of heat from high power electronics. The first problem deals with transferring heat from the electronic components into a heat carrier that carries the heat away from the components. The second problem relates to the transport of the large amount of heat, for example, 100 W to 100 kW from the source to the sink without significantly increasing the temperature of the heat carrier.

**[0005]** There are two types of systems commonly used for the removal of heat from the electronics: a passive cooling system and an active cooling system. In the passive cooling system, the thermal energy is dissipated to the heat sink without the help of a dynamic mechanical system. Examples of passive cooling systems are fin type heat sinks, heat spreaders, and heat pipes. Fin type heat sinks and heat spreaders being conduction based, cannot remove and transport a large amount of heat per unit surface area. Conduction is a slower mode of heat transport than convection and radiation. Heat pipes being based on latent heat of evaporation of a liquid and convection mode of heat transport, can remove and transport larger amounts of thermal energy. However, heat pipes too have a limited heat carrying ability because the convection process is natural and not forced.

**[0006]** Active cooling systems typically utilize a pump and a coolant to remove and transport thermal energy by forced convection. These systems can be designed to handle a single phase fluid or a two-phase fluid. In a single-phase fluid cooling system, the heat transport depends only on the sensible heat carried by the fluid, based on heat capacity of the fluid, whereas in a two-phase pumped fluid cooled system, the heat transport depends on the latent heat of evaporation or fusion carried by the fluid. Latent heat based systems typically transport more amount of thermal energy compared to the sensible heat based systems. However, the state of the art two-phase active cooling systems are limited by the natural convection of the vapor from the heat source to a heat sink, which reduces efficiency of the heat transportation system. Moreover, the

design of two-phase active cooling systems for high gravitational force environments and microgravity environments is extremely complicated.

**[0007]** Several techniques to improve the energy transport capabilities of single phase liquid cooling systems have been experimented with. For example, microencapsulated phase change materials have been added to the liquid coolant to form slurries which have a greater heat capacity due to the latent heat of fusion of the phase change material. However, the types of fluids typically have a low percentage of phase change material loading, often less than 5%, because higher concentrations of the phase change material will increase the viscosity of the fluid to a level that the fluid becomes difficult to pump. Microcapsules of the phase change material could also break due to impact with pump impellers and other components of the system. The microcapsules may further agglomerate under certain conditions and block fluid flow channels.

**[0008]** Dispersions of nanoparticles in the coolant, also referred to as nanofluids, have been investigated for use in cooling systems due to greater thermal conductivity. The greater improvement in the thermal conductivity is important in case of laminar flow of the coolant. In laminar flow, the heat transfer coefficient is directly proportional to the thermal conductivity of the coolant. Introduction of simple nanoparticles typically does not increase the heat carrying capacity of a coolant.

**[0009]** Hence, there is a need for an active multiphase heat transportation system that eliminates need for a pump and significantly improves the heat transfer and transport ability of the system.

### SUMMARY OF THE INVENTION

**[0010]** This summary is provided to introduce a selection of concepts in a simplified form that are further described in the detailed description of the invention. This summary is not intended to identify key or essential inventive concepts of the claimed subject matter, nor is it intended for determining the scope of the claimed subject matter.

**[0011]** The method and system disclosed herein addresses the above stated need for an active multiphase heat transportation system that eliminates need for a pump and significantly improves the heat transfer and transport ability of the system. The active multiphase heat transportation system disclosed herein comprises multiple containers, a guide track, and a drive system. The containers are, for example, hollow spherical, cylindrical, or cubical steel balls. The containers used in the active multiphase heat transportation system disclosed herein have a diameter ranging, for example, from about 10 nanometers to about 10 centimeters. The containers contain a phase change material in a first phase. The first phase is, for example, a solid phase or a liquid phase. The containers contain headspace for allowing expansion of the phase change material. The phase change material is selected from a group comprising, for example, metals, alloys, salts, salt mixtures, salt hydrates, polymers, hydrocarbons, silicones, fluorocarbons, hydrofluorocarbons, organic liquids, water, salt water solutions, and a combination thereof. The guide track leads from the heat source to the heat sink. The guide track is, for example, a tube filled with a non-flammable dielectric liquid.

**[0012]** The phase change material in the first phase in the containers absorbs heat from the heat source on establishing thermal contact with the heat source and changes to a second



phase. For example, the phase change material in a solid phase in the containers absorbs the heat from the heat source and changes to a liquid phase. In another example, the phase change material in a liquid phase in the containers absorbs the heat from the heat source and changes to a vapor phase. The phase change material absorbs the heat from the heat source via the non-flammable dielectric liquid. In an embodiment, a source plate is provided for transferring the heat from the heat source to the non-flammable dielectric liquid. The drive system moves the containers containing the phase change material in the second phase, for example, the liquid phase or the vapor phase to the heat sink along the guide track. The drive system comprises, for example, multiple electromagnetic coils, a cog with sphere engaging teeth driven by a motor, or a drive chain driven by a motor. In an embodiment, the drive system comprises multiple sets of the electromagnetic coils. The sets of the electromagnetic coils are activated in succession for moving the containers to the heat sink. In another embodiment, the drive chain operated by an external motor carries the containers to the heat sink. In another embodiment, a wheel with sphere engaging teeth is employed inside the guide track to move the containers along the guide track. The wheel is moved by, for example, a motor or a spinning magnet.

[0013] The phase change material in the second phase in each of the containers transfers the absorbed heat to the heat sink and changes to the first phase. For example, the phase change material in the liquid phase in each of the containers transfers the absorbed heat to the heat sink and changes to the solid phase. In another example, the phase change material in the vapor phase in each of the containers transfers the absorbed heat to the heat sink and changes to the liquid phase. The heat source is cooled due to the transportation of the heat from the heat source to the heat sink.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The foregoing summary, as well as the following detailed description of the invention, is better understood when read in conjunction with the appended drawings. For the purpose of illustrating the invention, exemplary constructions of the invention are shown in the drawings. However, the invention is not limited to the specific methods and instrumentalities disclosed herein.

[0015] FIG. 1 illustrates a method of transporting heat from a heat source to a heat sink.

[0016] FIG. 2 exemplarily illustrates a system for transporting heat from a heat source to a heat sink.

[0017] FIG. 3 exemplarily illustrates a drive system comprising three sets of electromagnetic coils for moving multiple containers along a guide track.

[0018] FIG. 4 exemplarily illustrates a list of potentially usable phase change materials with melting temperature and latent heat of fusion of each of the phase change materials.

[0019] FIG. 5 exemplarily illustrates a control system for the drive system.

[0020] FIG. 6A exemplarily illustrates thermal conduction between a source plate and a non-flammable dielectric liquid in a guide track.

[0021] FIG. 6B exemplarily illustrates thermal conduction between the non-flammable dielectric liquid in the guide track and the heat sink.

[0022] FIG. 7 exemplarily illustrates an embodiment of a drive system for moving multiple containers along a guide track.

#### DETAILED DESCRIPTION OF THE INVENTION

[0023] FIG. 1 illustrates a method of transporting heat from a heat source 204 to a heat sink 205. The heat source 204 is, for example, a microprocessor, any electronic component, solar radiation, a mechanical system that generates heat, etc. The heat sink 205 is, for example, a fan cooled radiator or a liquid cooled heat exchanger. A system 200 for transporting heat from a heat source 204 to a heat sink 205, herein referred to as an “active multiphase heat transportation system” 200 is exemplarily illustrated in FIG. 2. The active multiphase heat transportation system 200 comprising multiple containers 201, a guide track 202 leading from the heat source 204 to the heat sink 205, and a drive system 203 is provided 101. The containers 201 are disposed within the guide track 202.

[0024] The containers 201 are, for example, hollow spherical, cylindrical or cubical metal balls such as the commercially available steel balls manufactured by Industrial Tectonics Inc®. The containers 201 have different sizes. For example, the containers 201 used in the active multiphase heat transportation system 200 disclosed herein have a diameter ranging from about 10 nanometers to about 10 centimeters. The containers 201 contain a phase change material in a first phase 208a, for example, a solid phase or a liquid phase. As used herein, the term “phase change material” refers to a substance with a high heat of fusion or evaporation which is capable of storing and releasing large amounts of energy. These substances change phase from the solid phase to the liquid phase at the melting point or from the liquid phase to the vapor phase at the boiling point and vice versa. Heat is absorbed or released when the phase change material changes from a solid phase to a liquid phase or from a liquid phase to a vapor phase, and heat is emitted when the phase change material changes from the liquid phase to the solid phase or from a vapor phase to a liquid phase. The heat involved in the conversion of the phase is herein referred to as “latent heat”. The phase change material is selected from a group comprising, for example, metals, alloys, salts, salt mixtures, salt hydrates, polymers, hydrocarbons, silicones, fluorocarbons, hydrofluorocarbons (HFCs), organic liquids, water, salt water solutions, and a combination thereof.

[0025] Each of the containers 201 comprises a small hole through which the phase change material is introduced into each of the containers 201. A small headspace 601 is provided in each of the containers 201 to allow for expansion and contraction of the phase change material due to absorbed and emitted heat, as exemplarily illustrated in FIGS. 6A-6B. The hole is then re plugged with solder material and polished to create a smooth surface. The resultant density of each of the containers 201 after the introduction of the phase change material is close to the density of a non-flammable dielectric liquid 209 in the guide track 202 so that the weight of the containers 201 is balanced by the buoyancy in the non-flammable dielectric liquid 209. The resultant density of each of the containers 201 after the introduction of the phase change material is, for example, 1.5 to 2.0 g/cc.

[0026] As illustrated schematically in FIG. 2, the guide track 202 is a closed loop from the heat source 204 to the heat sink 205. The guide track 202 forms a loop from the heat source 204 to the heat sink 205 and back from the heat sink 205 to the heat source 204. The guide track 202 is, for

example, a tube filled with a liquid. In certain electronic cooling applications, a non-flammable dielectric liquid **209** may be desired to prevent fire and short-circuiting in case of a leak. The guide track **202** is, for example, made of aluminum. The guide track **202** is sealed during operation, and is fluid-tight to prevent escape of the non-flammable dielectric fluid **209**. The pressure inside the guide track **202** during operation is maintained at an optimum and does not affect the boiling properties of the non-flammable dielectric fluid **209**.

[0027] The non-flammable dielectric liquid **209** in the guide track **202** is, for example, a perfluorocarbon or a hydrofluorocarbon (HFC) with a boiling point of about 40° C. to 50° C. The non-flammable dielectric liquid **209** absorbs heat from the heat source **204** and starts boiling. The boiling liquid converts to vapor and condenses on the outsides of the containers **201** disposed within the guide track **202**, imparting the latent heat of vaporization to the phase change material in the first phase **208a** in the containers **201**. In an embodiment, the guide track **202** comprises temperature sensors **206** and **207** for measuring temperature of the non-flammable dielectric liquid **209** at different points along the guide track **202**. For example, the guide track **202** comprises a heat source temperature sensor **206** and a heat sink temperature sensor **207**. The temperature sensors **206** and **207** are positioned so as not to obstruct movement of the containers **201** within the guide track **202**. The guide track **202** is disassembled for changing or replenishing the non-flammable dielectric liquid **209** or the containers **201**. The guide track **202** further comprises a filling and draining port (not shown) for changing or replenishing the non-flammable dielectric liquid **209**. The guide track **202** further comprises a transparent section (not shown) for enabling visual observation of the containers **201** in motion within the guide track **202**.

[0028] The phase change material in the first phase **208a**, for example, a solid phase or a liquid phase in the containers **201** absorbs **102** the heat from the heat source **204** on establishing thermal contact with the heat source **204**. The phase change material in the first phase **208a** in the containers **201** changes to a second phase **208b** on the absorption of the heat. For example, the phase change material in the solid phase in the containers **201** changes to a liquid phase on the absorption of the heat. In another example, the phase change material in the liquid phase in the containers **201** changes to a vapor phase on the absorption of the heat. The phase change material used in this case is, for example, methanol, because of high latent heat of evaporation of approximately 1100 kJ/kg. Other potentially usable liquid to vapor phase change materials are fluorocarbon materials, acetone, and methylene chloride. If liquid to vapor phase change material is used in the containers **201**, the pressure inside the containers **201** should not affect the boiling point of phase change material significantly, which in turn depends on the amount of phase change material filled in each of the containers **201**. Liquid to vapor phase change materials within the containers **201** have higher latent heat as well as heat transfer coefficients. However, a greater amount of phase change material can be accommodated into the containers **201** if a solid to liquid phase change material is used. To enhance the heat transfer in solid to liquid phase change material, nanoparticles or carbon nanotubes may be incorporated in the phase change material to increase the thermal conductivity of the solid to liquid phase change material.

[0029] In an embodiment, the thermal contact is established via a source plate **605** and the non-flammable dielectric

liquid **209** in the guide track **202**, as exemplarily illustrated in FIG. 6A. FIG. 6A exemplarily illustrates thermal conduction between the source plate **605** and the non-flammable dielectric liquid **209** in the guide track **202**. The source plate **605** is attached to the aluminum skin of the guide track **202**. In another example, the guide track **202** is a part of the source plate **605**. The non-flammable dielectric liquid **209** is located on the other side of the aluminum skin of the guide track **202** from the source plate **605**. The source plate **605** is thermally connected to the heat source **204** and absorbs heat from the heat source **204**. The heat source **204** conducts heat to the source plate **605** and the source plate **605** conducts the heat to the guide track **202**. The source plate **605** thereby transfers heat **604** from the heat source **204** to the non-flammable dielectric liquid **209**. The phase change material in the first phase **208a** absorbs the heat **604** from the heat source **204** via the source plate **605** and the non-flammable dielectric liquid **209** in the guide track **202**. The boiling temperature of the non-flammable dielectric liquid **209** is slightly higher than the melting temperature of the phase change material.

[0030] The non-flammable dielectric liquid **209** is thermally connected to the source plate **605** and absorbs the heat **604** from the source plate **605**. The non-flammable dielectric liquid **209** absorbs the heat **604** in the form of both sensible heat, which raises the temperature of the non-flammable dielectric liquid **209**, and as latent heat which changes the non-flammable dielectric liquid **209** from the liquid phase **602** to a vapor phase **603**. The vapor thus obtained contains both the sensible heat and the latent heat of vaporization. The vapor condenses on the outer surfaces of the containers **201** containing the phase change material, thereby imparting the latent heat to the phase change material in the first phase **208a** in the containers **201**. By utilizing the non-flammable dielectric liquid **209** and the latent heat to impart heat **604** to the phase change material, large amounts of heat can be transferred to the phase change material without significantly raising the operating temperature of the phase change material. For example, up to 10 kilowatts of heat with a heat flux of about 1200 watts/cm<sup>2</sup> may be transferred. In addition to the heat from the heat source **204**, the non-flammable dielectric liquid **209** also absorbs and transfers to the phase change material waste heat from other minor heat sources, for example, heat leaked from different components. Critical heat flux of the non-flammable dielectric liquid **209** is optimized to obtain a heat dissipation value of approximately 500 W/cm<sup>2</sup> to 2000 W/cm<sup>2</sup>.

[0031] The drive system **203** moves **103** the containers **201** containing the phase change material in the second phase **208b**, for example, the liquid phase or the vapor phase, to the heat sink **205** along the guide track **202**. In an embodiment, the drive system **203** comprises multiple electromagnetic coils **203a**.

[0032] Where the drive system **203** comprises multiple sets of the electromagnetic coils **203a**, the sets of the electromagnetic coils **203a** are activated in succession for moving the containers **201** to the heat sink **205**. Consider an example where the drive system **203** comprises three sets **203b**, **203c**, and **203d** of electromagnetic coils **203a** as exemplarily illustrated in FIG. 3.

[0033] The first set **203b** of electromagnetic coils **203a** from the electromagnetic coils **203a** is first activated. The electromagnetic coils **203a** are activated by passing a current through each of the electromagnetic coils **203a**. Each of the electromagnetic coils **203a** produces a controlled magnetic

field within the guide track **202**, when a current passes through electromagnetic coils **203a**. The strength of the magnetic field, represented herein by “B”, is calculated using the formula  $B = \mu_o i_o n$ , where  $\mu_o$  is the permeability constant  $= 4\pi \times 10^{-7}$  Tesla Meter/Ampere,  $i_o$  is the current in the electromagnetic coil, and  $n$  is the number of loops or turns in the electromagnetic coil. Direction of the magnetic field depends on direction of the current in the electromagnetic coil. Hence, the magnetic field can be reversed by reversing the direction of the current. The magnetic field produces a force that acts on the containers **201**. The force is proportional to the magnetic field strength.

[0034] In FIG. 3, the individual electromagnetic coils **203a** from the first set **203b** are labeled with the numeral “1”. The containers **201** containing the phase change material in the second phase **208b**, for example, the liquid phase or the vapor phase are magnetically attracted to the closest electromagnetic coil from the first set **203b** of electromagnetic coils **203a**. Each of the containers **201** containing the phase change material in the second phase **208b** tries to move towards the closest electromagnetic coil from the first set **203b**. Since movement of the containers **201** is limited within the guide track **202**, each of the containers **201** containing the phase change material orients itself so that the center of the container **201** is directly underneath the closest electromagnetic coil from the first set **203b**.

[0035] The first set **203b** of electromagnetic coils **203a** is then deactivated and a second set **203c** of electromagnetic coils **203a** from the electromagnetic coils **203a** is activated. In FIG. 3, the individual electromagnetic coils **203a** from the second set **203c** are labeled with the numeral “2”. The containers **201** containing the phase change material in the second phase **208b** are now magnetically attracted to the closest electromagnetic coil from the second set **203c** of electromagnetic coils **203a**. Each of the containers **201** containing the phase change material in the second phase **208b** tries to move towards the closest electromagnetic coil from the second set **203c**. Each of the containers **201** containing the phase change material now orients itself so that the center of the container **201** is directly underneath the closest electromagnetic coil from the second set **203c**.

[0036] The second set **203c** of electromagnetic coils **203a** is then deactivated and a third set **203d** of electromagnetic coils **203a** from the electromagnetic coils **203a** is activated. In FIG. 3, the individual electromagnetic coils **203a** from the third set **203d** are labeled with the numeral “3”. The containers **201** containing the phase change material in the second phase **208b** are now magnetically attracted to the closest electromagnetic coil from the third set **203d**. Each of the containers **201** containing the phase change material in the second phase **208b** tries to move towards the closest electromagnetic coil from the third set **203d**. Each of the containers **201** containing the phase change material now orients itself so that the center of the container **201** is directly underneath the closest electromagnetic coil from the third set **203d**. The successive orientation of the containers **201** underneath the electromagnetic coils **203a** from the first set **203b**, the second set **203c** and the third set **203d**, results in a substantially linear motion of the containers **201** within the guide track **202**.

[0037] Therefore in this example, by successively activating the three sets **203b**, **203c**, and **203d** of electromagnetic coils **203a**, each of the containers **201** is moved from a position directly underneath an electromagnetic coil from the first set **203b** to a position directly underneath an electromagnetic

coil from the third set **203d**. By reactivating the three sets **203b**, **203c**, and **203d** successively in the same order at a predetermined frequency, each of the containers **201** can be continually moved along the guide track **202** from the heat source **204** to the heat sink **205**. In an example, to sustain a high heat flux, the containers **201** are moved at a predetermined speed in the order of 0.1 meters per second. The motion of the containers **201** along the guide track **202** helps to mechanically scour the vapor bubbles, formed due to the boiling non-flammable dielectric liquid **209**, from the outer surfaces of the containers **201**. In an embodiment, the system **200** comprises a guide track **202** of square cross-section and cylindrical containers **201** to enable higher heat transfer per unit volume of the guide track **202**.

[0038] In an embodiment, a control system **501** with a power supply **502** as illustrated in FIG. 5 is optionally used to operate the sets **203b**, **203c**, and **203d** of electromagnetic coils **203a**. The strength of the current passing through the electromagnetic coils **203a**, and hence the strength of the magnetic field is variably controlled by the control system **501**. Temperature sensors, for example, the heat source temperature sensor **206** and the heat sink temperature sensor **207** are placed along specific points on the guide track **202** to detect temperatures at those points. The placement of the temperature sensors **206** and **207** is, for example, near the heat source **204** and the heat sink **205** as exemplarily illustrated in FIG. 2. The heat source temperature sensor **206** and the heat sink temperature sensor **207** are connected to the control system **501** and monitor the temperatures at the heat source **204** and the heat sink **205**. The strength of the magnetic field or the frequency of activation of the three sets **203b**, **203c**, and **203d** of electromagnetic coils **203a** is varied by a feedback control of the control system **501** based on the monitored temperatures. Hence, the feedback control of the control system **501** determines the speed of movement of the containers **201** within the guide track **202**, and hence the amount of heat transferred between the heat source **204** and the heat sink **205**. The control system **501** also regulates the speed of the fan **503** in the heat sink **205**.

[0039] In another embodiment, the drive system **203** comprises a drive chain (not shown) or a drive belt (not shown) present along the entire length of the guide track **202** from the heat source **204** to the heat sink **205** and back from the heat sink **205** to the heat source **204**, including the portion of the guide track **202** in thermal contact with the heat source **204** and the heat sink **205**. The drive chain or a drive belt carries the containers **201** to the heat sink **205**. The containers **201** are placed on the drive chain or the drive belt. The drive chain or the drive belt is, for example, driven using a prime mover (not shown) such as a motor and a gear system. In an embodiment, the containers **201**, for example, the hollow balls are shaped to form links in a chain as illustrated in FIG. 7. The container chain is, for example, driven using a prime mover such as a motor and a gear system. The container chain comprises the hollow balls connected together using short lengths of strings **701**. In this embodiment, the drive system **203** comprises a wheel with sphere engaging teeth **703** employed inside the guide track **202** to move the containers **201** along the guide track **202**. A single cog with the sphere-engaging teeth **703** and driven by a motor drives the container chain. FIG. 7 illustrates a section **702** of a cog wheel, wherein the sphere-engaging teeth **703** engage the hollow balls. To avoid penetration of the sealed guide track **202** by the cog or a drive

shaft of the motor, the drive power is transmitted using, for example, a spinning magnet (not shown) to drive the cog.

[0040] The phase change material in the second phase **208b** in each of the containers **201** transfers **104** the absorbed heat to the heat sink **205** and changes to the first phase **208a**. For example, the phase change material in the liquid phase in each of the containers **201** transfers the absorbed heat to the heat sink **205** and changes to the solid phase. In another example, the phase change material in the vapor phase in each of the containers **201** transfers the absorbed heat to the heat sink **205** and changes to the liquid phase. In an embodiment, the heat sink **205** is a radiator cooled by a fan **503**. In another embodiment, the heat sink **205** is a liquid cooled heat exchanger. The heat sink **205** comprises a metal structure with fins. The metal used in the heat sink **205** has high thermal conductivity and the fins provide a large surface area. The heat sink **205** is in direct thermal contact with, for example, the aluminum skin of the guide track **202**. The guide track **202** may also be a part of the heat sink **205**. The non-flammable dielectric liquid **209** in the guide track **202** at the heat sink **205** is in thermal contact with the heat sink **205** via the aluminum skin of the guide track **202**, and therefore is at a lower temperature than the phase change material in the second phase **208b** in the containers **201**. When the containers **201** reach the heat sink **205**, the phase change material transfers the absorbed heat to the non-flammable dielectric liquid **209** at the lower temperature. FIG. 6B exemplarily illustrates thermal conduction between the non-flammable dielectric liquid **209** in the guide track **202** and the heat sink **205**. The transfer of heat **604** between the phase change material in the second phase **208b** and the heat sink **205** is exemplarily illustrated in FIG. 6B. The heat transfer **604** near the heat sink **205** occurs as the heat transfer **604** occurring at the heat source **204**, but in the reverse direction. The heat sink **205** absorbs the heat **604** from the non-flammable dielectric liquid **209** and dissipates the heat, for example, into the atmosphere using the fan **503**.

[0041] The containers **201** at the heat sink **205** now contain the phase change material in the first phase **208a**, for example, the solid phase or the liquid phase. The drive system **203** moves the containers **201** back towards the heat source **204**. When the containers **201** reach the heat source **204**, the phase change material in the first phase **208a** is ready to absorb the heat from the heat source **204** again. The heat source **204** is therefore cooled due to the transportation of the heat from the heat source **204** to the heat sink **205**.

[0042] In the case of the electromagnetic coils **203a**, the drive system **203** is not present along the portion of the guide track **202** in thermal contact with the heat source **204** and the heat sink **205**.

[0043] Since there are no electromagnetic coils **203a** along the portion of the guide track **202** in thermal contact with the heat source **204**, the containers **201** in that portion of the guide track **202** will not be moved by magnetic attraction. However, the containers **201** in the portion of the guide track **202** immediately upstream of the portion in thermal contact with the heat source **204** are moved due to magnetic attraction and hence will exert a force on the containers **201** in the portion in thermal contact with the heat source **204**, causing the containers **201** to move. As illustrated in FIG. 2, the containers **201** travel through a U-shaped turn in the guide track **202** near the heat source **204**, the force exerted on each successive container drops. After undergoing a 180 degree turn, for example, after 4 turns of 45 degrees each, the resultant force on the containers **201** leaving the portion in thermal contact

with the heat source **204** is approximately 25% (Cosine  $45 \times$  Cosine  $45 \times$  Cosine  $45 \times$  Cosine  $45$ ) of the original force exerted by the containers **201** entering the portion in thermal contact with the heat source **204**. The force is enough to transport the containers **201** out of the portion in thermal contact with the heat source **204** without the help of a magnetic field along the portion in thermal contact with the heat source **204**.

[0044] Frictional force between the containers **201** and inner walls of the guide track **202** is insignificant because the containers **201** are almost floating in the non-flammable dielectric liquid **209** in the guide track **202** liquid owing to the small difference in density. Under the earth's gravitational field as well as in a microgravity environment, there will be very little frictional force, whereas, under high gravitational acceleration (high g) conditions the frictional force may be amplified. However, in case of applications like aeronautics, the high g conditions typically exist only for a few minutes during take-offs. In the high g conditions, drag force exerted on the balls by the non-flammable dielectric liquid **209** may be significant enough to consider. However, using low viscosity liquids, for example, fluorocarbons, will cause generation of lower drag forces.

[0045] The speed of motion of the containers **201** along the guide track **202** depends on the magnetic field generated by the electromagnetic coils **203a**. The magnetic field in turn depends on current passed through the electromagnetic coils **203a**. When current passes through the electromagnetic coils **203a**, resistive heat is generated. The resistive heat is computed as  $i^2R$ , where "i" is the current flowing through the electromagnetic coils **203a** and "R" is the resistance of the electromagnetic coils **203a**. The generated resistive heat could be detrimental to the system **200** and possibly degrade surrounding insulating materials. Increasing the number of turns in the electromagnetic coils **203a** would increase the magnetic strength generated by a lower current, but at the same time would increase the size and the weight of the system **200**. Therefore, an optimum level of the magnetic strength is reached in order to move the containers **201** at a required minimum velocity.

[0046] The design of the system **200** disclosed herein incorporates the advantages of a heat pipe and an active liquid cooled system with a very high loading of the phase change material. The system **200** works like a heat pipe with a forcibly increased heat transfer capacity. To maximize efficiency, the system **200** is well insulated except for the sections where heat is transferred from one component to another.

[0047] FIG. 4 exemplarily illustrates a list of potentially usable phase change materials with melting temperature  $T_{melting}$  and latent heat of fusion of each of the phase change materials. The potentially usable phase change materials are, for example, eicosane, pentacosane, tritriacontane, camphene, (+)-camphene, and (-)-camphene. The phase change material is selected based on predetermined criteria, for example, latent heat of fusion or evaporation, phase transition temperature in a predefined temperature range, narrow phase transition temperature range, compatibility with steel, and ready availability. Among the phase change materials listed in FIG. 4, (-)-camphene, (+)-camphene, camphene, and eicosane are the most suitable phase change materials based on temperature range, high latent heat of fusion, availability, and cost criteria. All the phase change materials illustrated in FIG. 4 are compatible with carbon steel.

[0048] Consider an example where a microprocessor inside a computer is cooled using the active multiphase heat transportation system 200 disclosed herein. In this example, the active multiphase heat transportation system 200 comprises a copper heat exchanger with channels as the heat source 204, an aluminum tube (1/4" inside diameter) as the guide track 202, hollow carbon steel spheres (3/16" outside diameter) as the containers 201 containing eicosane as the phase change material, and an aluminum radiator with a fan 503 as the heat sink 205. In this example, the copper heat exchanger being the heat source 204 is referred to by the numeral 204, the aluminum tube being the guide track 202 is referred to by the numeral 202, the hollow carbon steel spheres being the containers 201 are referred to by the numeral 201, and the aluminum radiator 205 being the heat sink 205 is referred to by the numeral 205. The microprocessor in the computer is attached to the copper heat exchanger 204. The aluminum tube 202 forms a closed loop from the copper heat exchanger 204 to the aluminum radiator 205 and back from the aluminum radiator 205 to the copper heat exchanger 204. The aluminum tube 202 in this example has three electromagnetic coils 203a arranged as illustrated in FIG. 3. The aluminum tube 202 and the channels inside the copper heat exchanger 204 and the aluminum radiator 205 are filled with an HFC fluid having a boiling point of 40° C.

[0049] The microprocessor produces heat during its operation and boils the HFC fluid when the temperature of the heated surface reaches 40° C. The hollow carbon steel spheres 201 are moved at a speed of 0.1 m/s inside the aluminum tube 202 and the channels by the electromagnetic force from the three electromagnetic coils 203a being turned ON and OFF in a particular order as described in the detailed description of FIG. 3. The vapor bubbles generated from the boiling HFC fluid rise up and come in contact with the colder hollow carbon steel spheres 201 and then condense on the surface at 40° C. The latent heat of evaporation is transferred to the hollow carbon steel spheres 201 and the eicosane present inside the hollow carbon steel spheres 201 starts to melt at about 36° C. The hollow carbon steel spheres 201 containing the molten eicosane move through the channels in the copper heat exchanger 204 and then through the aluminum tube 202 to the aluminum radiator 205. When the hollow carbon steel spheres 201 reach the aluminum radiator 205, they come in contact with the colder HFC fluid (colder than 30° C.) in the surrounding. The molten eicosane starts to transfer heat to the HFC fluid and in the process the molten eicosane undergoes a phase change from the liquid phase to the solid phase. The heat from the HFC fluid is transferred to the fins of the aluminum radiator 205 and then to the ambient air by means of the fan 503. The heat from the microprocessor is therefore transferred to the ambient air with a series of phase change processes.

[0050] The foregoing examples have been provided merely for the purpose of explanation and are in no way to be construed as limiting of the present invention disclosed herein. While the invention has been described with reference to various embodiments, it is understood that the words, which have been used herein, are words of description and illustration, rather than words of limitation. Further, although the invention has been described herein with reference to particular means, materials and embodiments, the invention is not intended to be limited to the particulars disclosed herein; rather, the invention extends to all functionally equivalent structures, methods and uses, such as are within the scope of

the appended claims. Those skilled in the art, having the benefit of the teachings of this specification, may effect numerous modifications thereto and changes may be made without departing from the scope and spirit of the invention in its aspects.

I claim:

1. A method of transporting heat from a heat source to a heat sink, comprising the steps of:

providing a plurality of containers containing a phase change material in a first phase, a guide track leading from said heat source to said heat sink, and a drive system;

absorbing said heat from said heat source by said phase change material in said first phase in said containers on establishing thermal contact with said heat source, wherein said phase change material in said first phase in said containers changes to a second phase on said absorption of said heat;

moving said containers containing said phase change material in said second phase to said heat sink along said guide track by said drive system; and

transferring said absorbed heat by said phase change material in said second phase in each of said containers to said heat sink, wherein said phase change material in said containers in said second phase changes to said first phase on said transfer of said absorbed heat;

whereby said heat source is cooled due to said transportation of said heat from said heat source to said heat sink.

2. The method of claim 1, wherein said first phase is a solid phase and said second phase is a liquid phase.

3. The method of claim 1, wherein said first phase is a liquid phase and said second phase is a vapor phase.

4. The method of claim 1, wherein said phase change material is selected from a group comprising metals, alloys, salts, salt mixtures, salt hydrates, polymers, hydrocarbons, silicones, fluorocarbons, hydrofluorocarbons, organic liquids, water, salt water solutions, and a combination thereof.

5. The method of claim 1, wherein said guide track is a tube filled with a non-flammable dielectric liquid.

6. The method of claim 5, wherein said phase change material in each of said containers absorbs said heat from said heat source via said non-flammable dielectric liquid.

7. The method of claim 5, further comprising the step of providing a source plate for transferring said heat from said heat source to said non-flammable dielectric liquid.

8. The method of claim 1, wherein said drive system comprises a plurality of sets of electromagnetic coils, wherein said sets of said electromagnetic coils are activated in succession for moving said containers to said heat sink.

9. The method of claim 1, wherein said drive system comprises a drive chain for carrying said containers to said heat sink.

10. The method of claim 1, wherein said drive system comprises a wheel with sphere engaging teeth employed inside said guide track to move said containers along said guide track, wherein said wheel is moved by one of a motor and a spinning magnet.

11. The method of claim 1, wherein said containers are hollow balls of one of a spherical shape, a cylindrical shape, and a cubical shape.

12. The method of claim 1, wherein said containers have a diameter ranging from about 10 nanometers to about 10 centimeters.

**13.** The method of claim **1**, wherein said containers contain headspace for allowing expansion of said phase change material.

**14.** A system for transporting heat from a heat source to a heat sink, comprising:

a plurality of containers containing a phase change material in a first phase, wherein said phase change material in said first phase in said containers absorb said heat from said heat source on establishing thermal contact with said heat source, wherein said phase change material in said first phase in said containers changes to a second phase on said absorption of said heat;

a guide track leading from said heat source to said heat sink; and

a drive system for moving said containers containing said phase change material in said second phase to said heat sink along said guide track.

**15.** The system of claim **14**, wherein said first phase is a solid phase and said second phase is a liquid phase.

**16.** The system of claim **14**, wherein said first phase is a liquid phase and second phase is a vapor phase.

**17.** The system of claim **14**, wherein said guide track is a tube filled with a non-flammable dielectric liquid.

**18.** The system of claim **17**, wherein said phase change material in each of said containers absorbs said heat from said heat source via said non-flammable dielectric liquid.

**19.** The system of claim **17**, further comprising a source plate for transferring said heat from said heat source to said non-flammable dielectric liquid.

**20.** The system of claim **14**, wherein said drive system comprises a plurality of sets of electromagnetic coils, wherein said sets of said electromagnetic coils are activated in succession for moving said containers to said heat sink.

**21.** The system of claim **14**, wherein said drive system comprises a drive chain for carrying said containers to said heat sink.

**22.** The system of claim **14**, wherein said drive system comprises a wheel with sphere engaging teeth employed inside said guide track to move said containers along said guide track, wherein said wheel is moved by one of a motor and a spinning magnet.

**23.** The system of claim **14**, wherein said containers are hollow balls of one of a spherical shape, a cylindrical shape, and a cubical shape, wherein said containers contain headspace for allowing expansion of said phase change material.

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