US 20130098354A1

(19) **United States**

(12) **Patent Application Publication**

Kummamuru

(10) **Pub. No.: US 2013/0098354 A1**

(43) **Pub. Date: Apr. 25, 2013**

(54) **SOLAR COLLECTORS**

(75) Inventor: **Ravi K. Kummamuru**, Hyderabad (IN)

(73) Assignee: **AXISOL INC.**, Santa Clara, CA (US)

(21) Appl. No.: **13/637,432**

(22) PCT Filed: **Apr. 15, 2011**

(86) PCT No.: **PCT/US11/32769**

§ 371 (c)(1),
(2), (4) Date: **Dec. 10, 2012**

Related U.S. Application Data

(60) Provisional application No. 61/324,730, filed on Apr. 15, 2010.

Publication Classification

(51) **Int. Cl.**

F24J 2/38	(2006.01)
F24J 2/46	(2006.01)
F24J 2/10	(2006.01)
F24J 2/26	(2006.01)

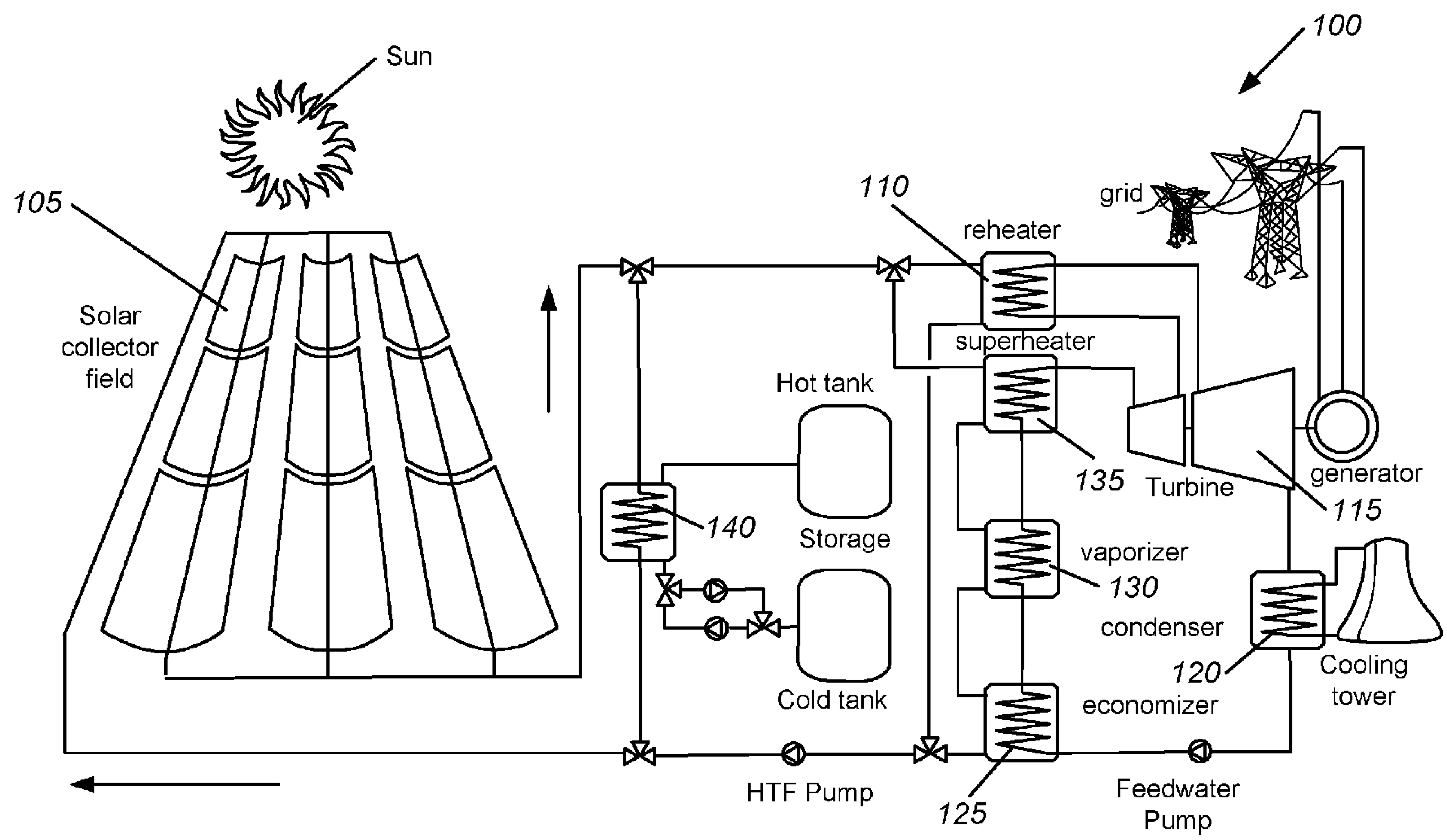
(52) **U.S. Cl.**

CPC ***F24J 2/38*** (2013.01); ***F24J 2/26*** (2013.01); ***F24J 2/4654*** (2013.01); ***F24J 2/10*** (2013.01)

USPC **126/600**; 126/674; 126/678; 126/684; 126/651

(57) **ABSTRACT**

An array of solar collectors includes dual axis reflectors for directing solar radiation to receivers at focal points of the reflectors. Solar radiation is used to heat a thermal energy storage material, which may be used to generate steam for use in power generation with the aid of a turbine. The dual axis reflectors may pivot about independent axes of rotation, thereby enabling use of the reflectors throughout the year.



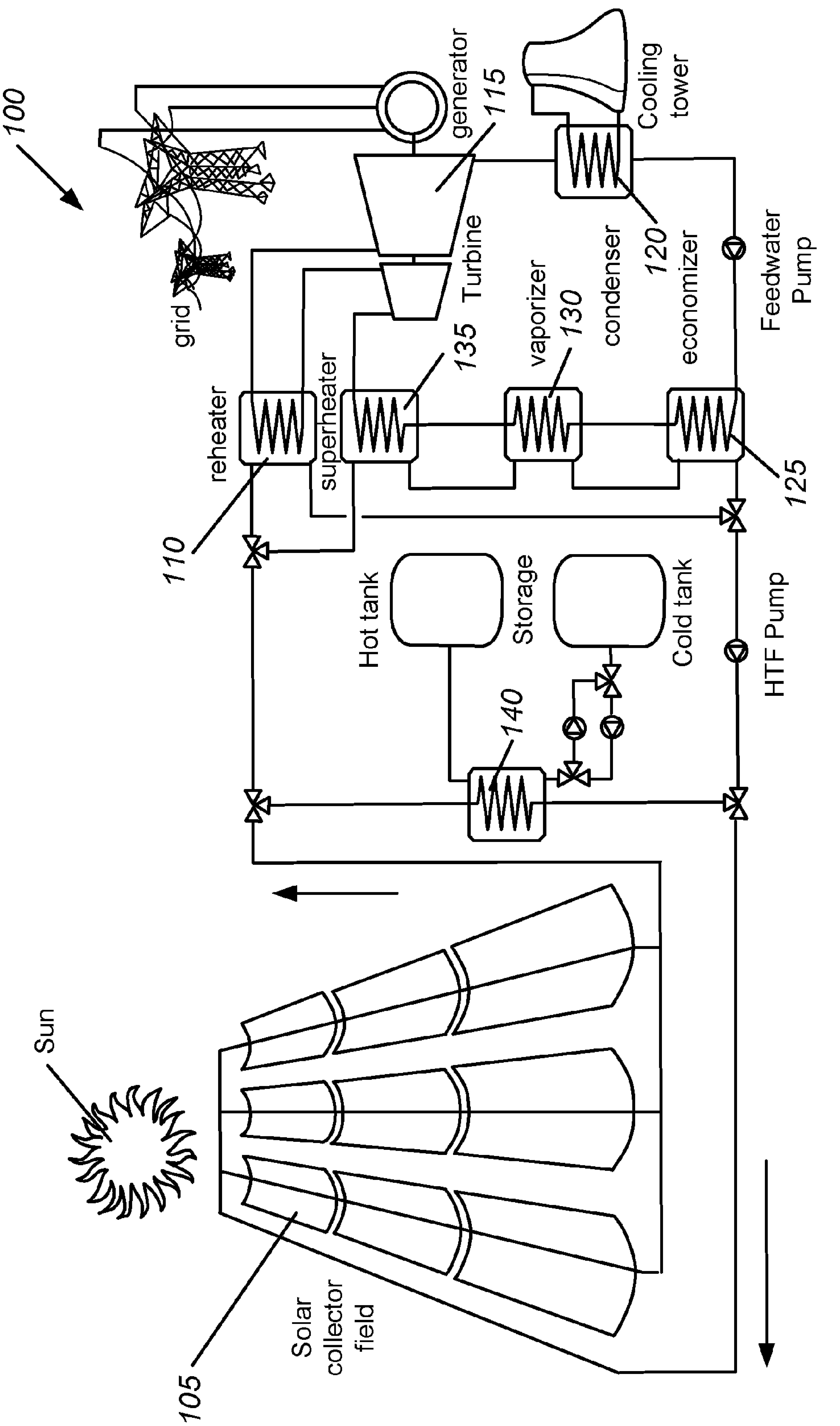

100
grid
generator
115
Cooling
tower
Turbine
reheater
superheater
135
vaporizer
130
condenser
120
economizer
Feedwater
Pump
125
110
Hot tank
Storage
Cold tank
HTF Pump
140
Sun
Solar
collector
field
105

FIG. 1

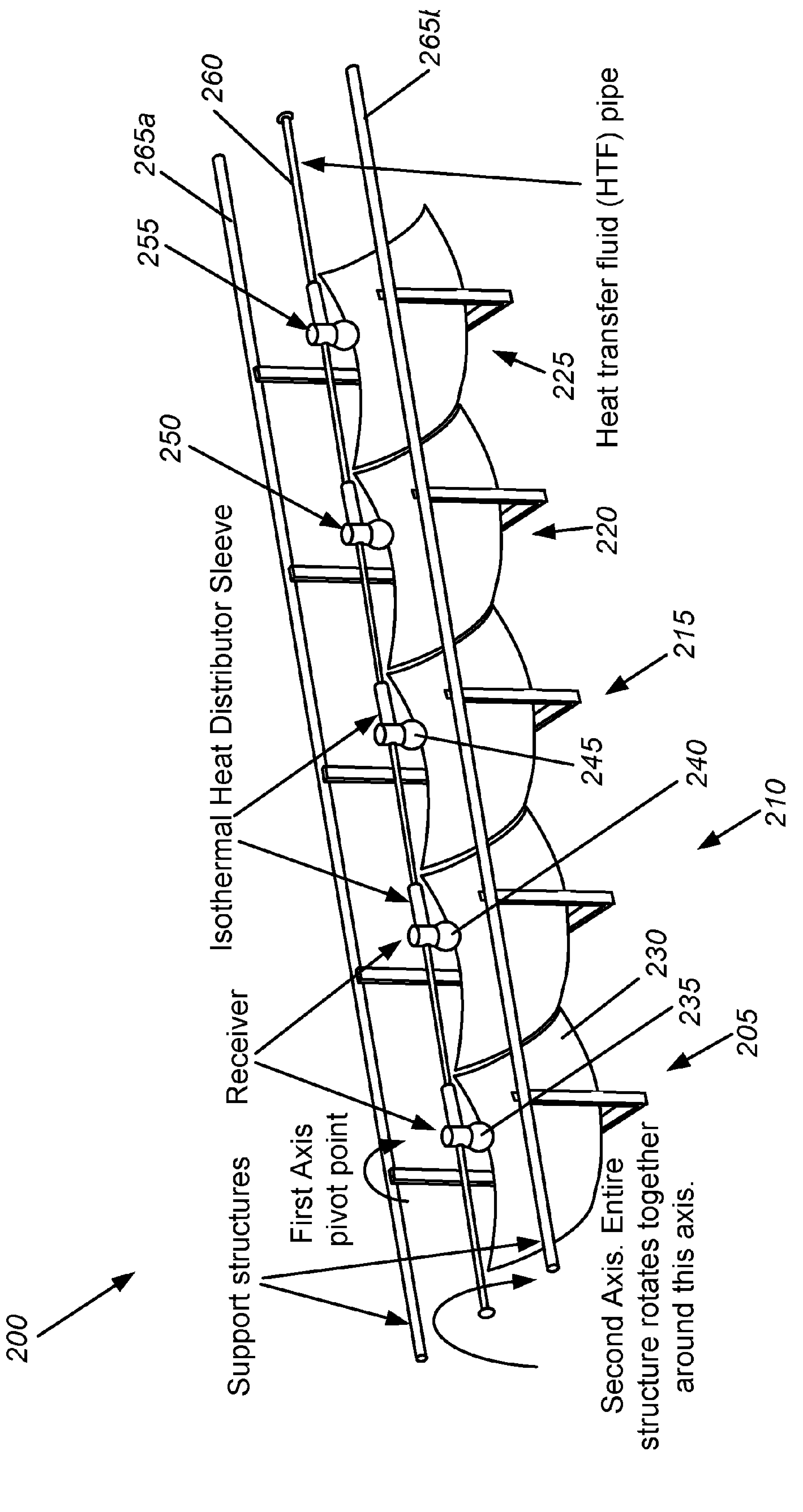

200
Support structures
First Axis pivot point
Receiver
Isothermal Heat Distributor Sleeve
Second Axis. Entire structure rotates together around this axis.
265a
255
250
260
265
Heat transfer fluid (HTF) pipe
225
220
215
245
240
210
230
235
205

FIG. 2

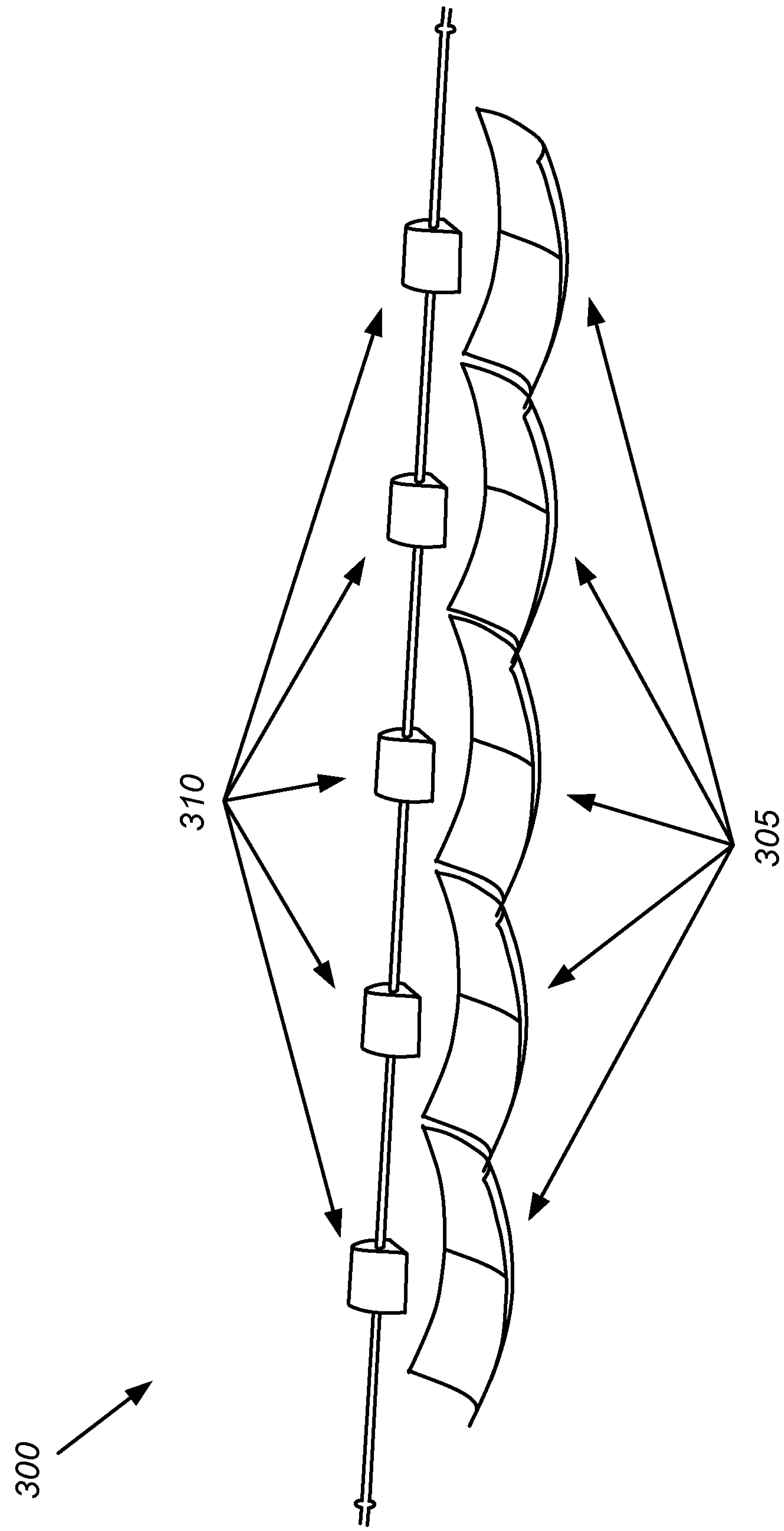


FIG. 3

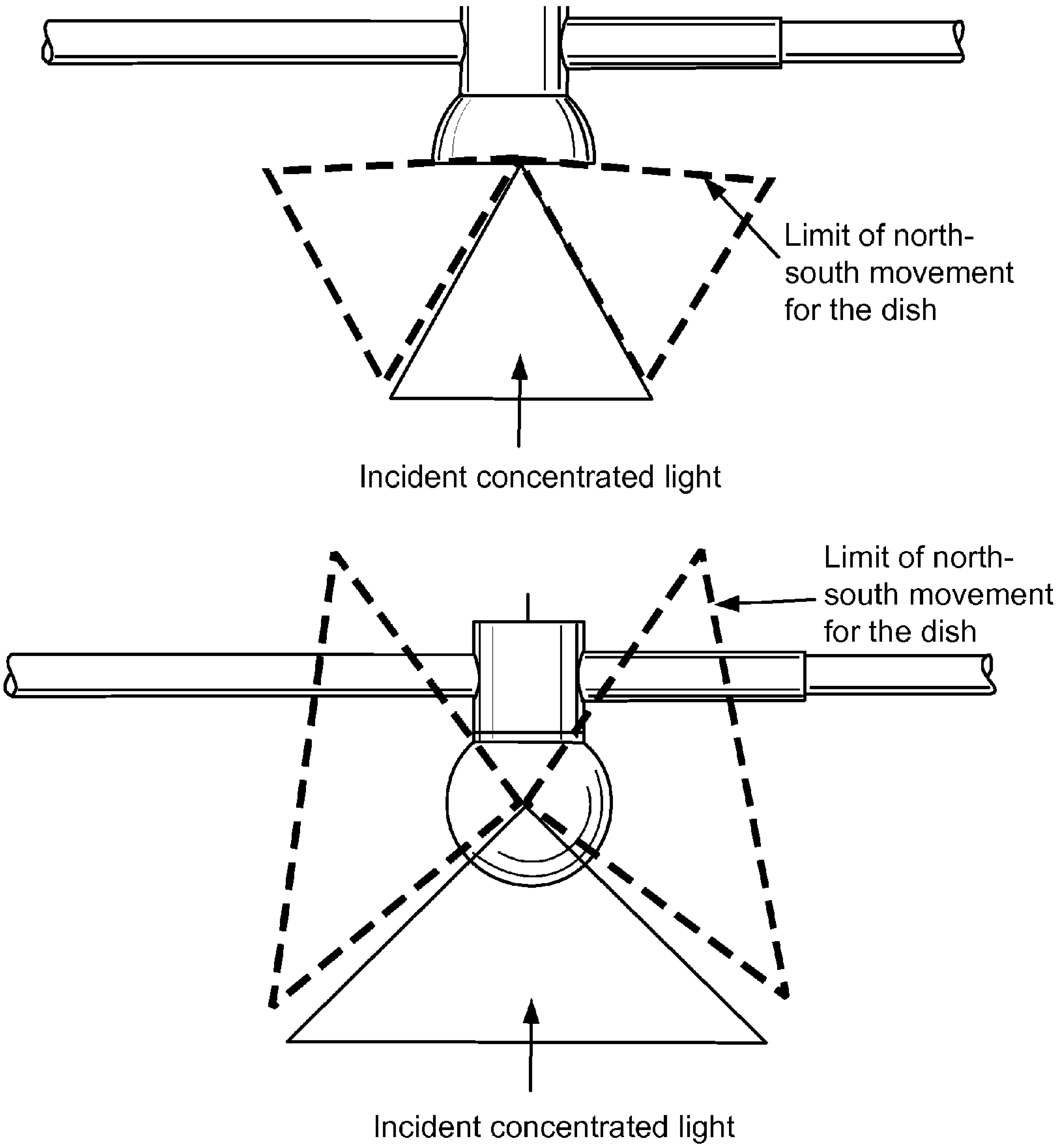

Limit of north-
south movement
for the dish
Incident concentrated light
Limit of north-
south movement
for the dish
Incident concentrated light

FIG. 4

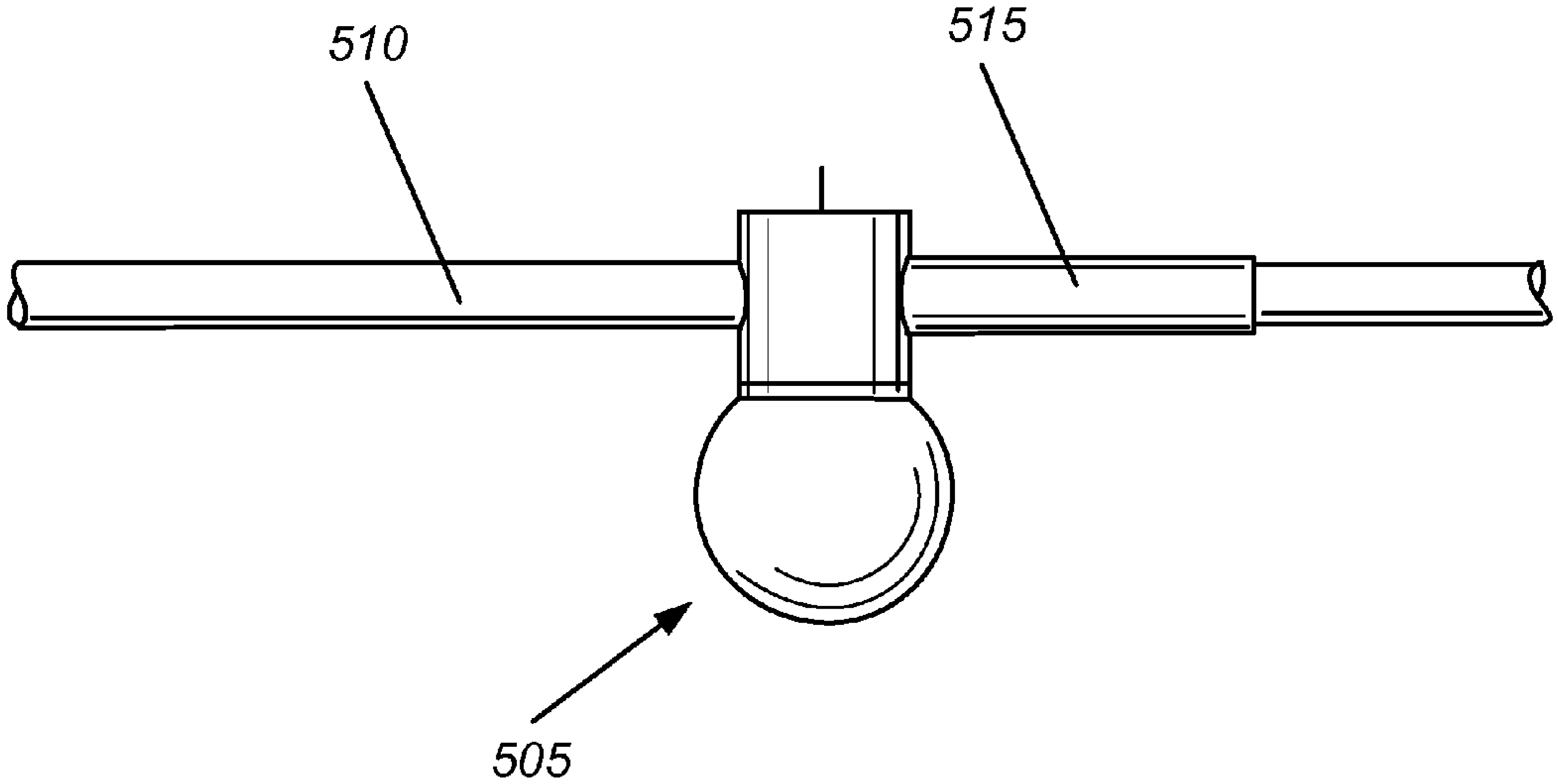


FIG. 5

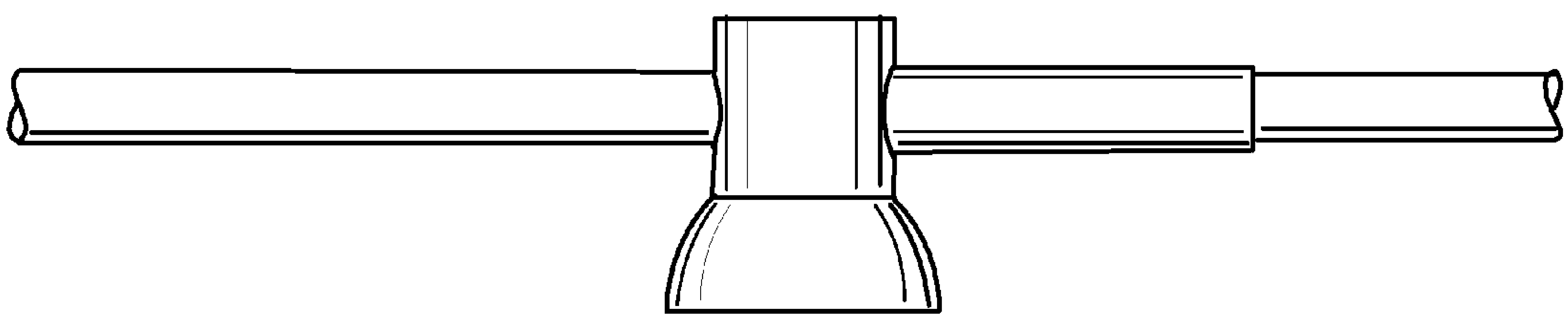


FIG. 6

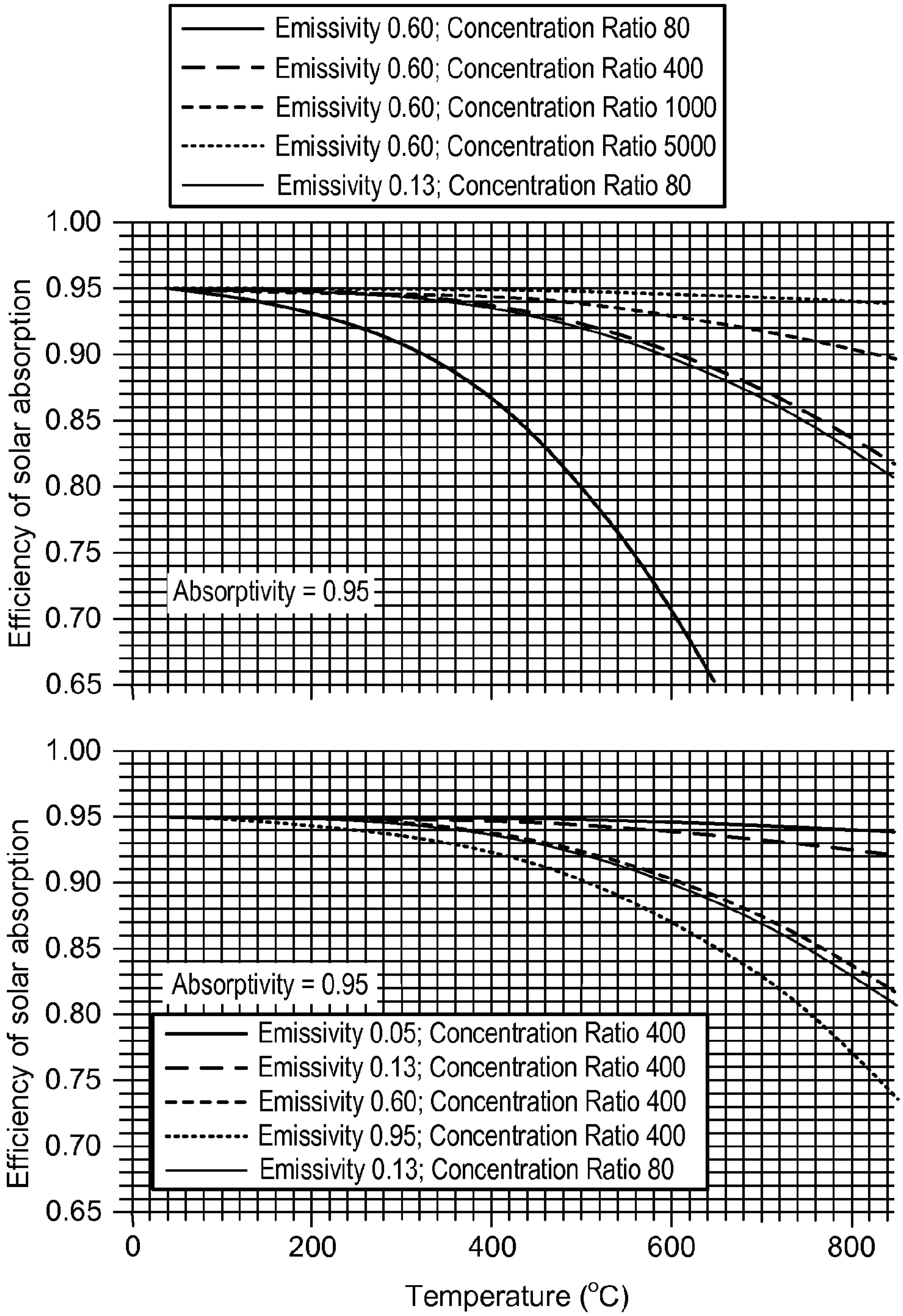

Emissivity 0.60; Concentration Ratio 80
Emissivity 0.60; Concentration Ratio 400
Emissivity 0.60; Concentration Ratio 1000
Emissivity 0.60; Concentration Ratio 5000
Emissivity 0.13; Concentration Ratio 80
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
Efficiency of solar absorption
Absorptivity = 0.95
Absorptivity = 0.95
Emissivity 0.05; Concentration Ratio 400
Emissivity 0.13; Concentration Ratio 400
Emissivity 0.60; Concentration Ratio 400
Emissivity 0.95; Concentration Ratio 400
Emissivity 0.13; Concentration Ratio 80
0
200
400
600
800
Temperature (°C)

FIG. 7

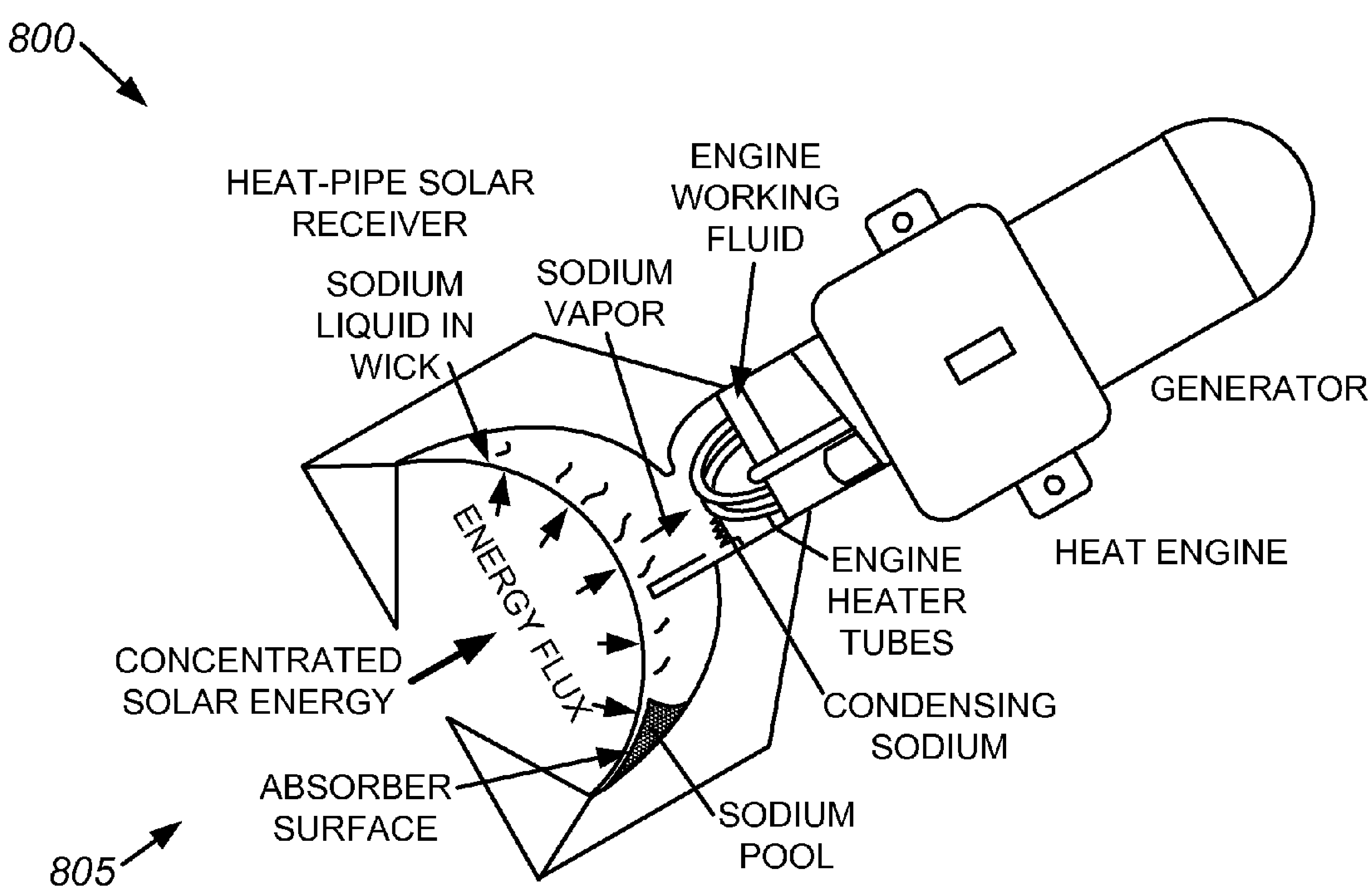

800
HEAT-PIPE SOLAR RECEIVER
ENGINE WORKING FLUID
SODIUM LIQUID IN WICK
SODIUM VAPOR
GENERATOR
ENERGY FLUX
HEAT ENGINE
ENGINE HEATER TUBES
CONCENTRATED SOLAR ENERGY
CONDENSING SODIUM
ABSORBER SURFACE
SODIUM POOL
805

FIG. 8

SOLAR COLLECTORS

CROSS-REFERENCE

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/324,730, filed on Apr. 15, 2010, which is entirely incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] Solar energy may be collected and converted into other forms of energy. Photovoltaic devices may convert photons into electrical energy, while solar thermal devices convert sunlight into heat energy.

[0003] Currently, a central receiver solar power system may consist of an array of heliostat mounted mirrors that track the motion of the sun and focus light to a central point at the top of a tower. The pointing accuracy of the heliostat mirrors is a key parameter that may affect the ultimate performance of the system and determines the concentration ratio (or efficiency) the system may achieve. Ultimately, this may affect the maximum temperature that may be achieved at the receiver placed at the top of the tower in thermal systems.

[0004] Solar central receiver tower systems may be built as dedicated facilities on large scale (e.g., tens to hundreds of megawatts per tower) away from population centers using solar thermal technology. Currently, solar towers are massive structures that may use a considerable amount of materials, which may lead to high startup and maintenance costs.

SUMMARY OF THE INVENTION

[0005] In one aspect of the invention, a solar collector comprises a heat transfer tube having a thermal energy transfer and/or storage material (also "energy storage material" herein); a receiver disposed along the heat transfer tube, the receiver for directing solar radiation to the thermal energy storage material; and a reflector supported by a support structure, the reflector for focusing solar radiation at the receiver, the reflector for collecting and focusing solar radiation along dual axes.

[0006] In some embodiments, a solar collector comprises a plurality of dual axis solar reflectors supported by a reflector support structure, each of the plurality of solar reflectors for focusing solar radiation at one of a plurality of receivers disposed along a heat transfer tube for conveying a thermal energy storage material. In cases in which the solar collector includes three or more solar reflectors, the plurality of solar reflectors ("reflectors") may be disposed in-line with one another.

[0007] In another aspect of the invention, a system for collecting solar radiation comprises a heat transfer tube having a thermal energy storage material; a plurality of receivers at discrete points along the heat transfer tube, each of the plurality of receivers for directing solar radiation to the thermal energy storage material; and a plurality of reflectors supported by a reflector support structure, the plurality of reflectors disposed near or adjacent one another, each of the plurality of reflectors for collecting and focusing solar radiation at one of the plurality of receivers, each of the plurality of reflectors for rotating along dual axes.

INCORPORATION BY REFERENCE

[0008] All publications, patents, and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication, patent, or patent application was specifically and individually indicated to be incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The novel features of the invention are set forth with particularity in the appended claims. A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the invention are utilized, and the accompanying drawings of which:

[0010] FIG. **1** schematically illustrates a system for collecting solar radiation and generating power in accordance with an embodiment of the invention;

[0011] FIG. **2** schematically illustrates an array of solar collectors, in accordance with an embodiment of the invention;

[0012] FIG. **3** schematically illustrates an array of solar collectors, in accordance with an embodiment of the invention;

[0013] FIG. **4** schematically illustrates a concave receiver (top) and spherical receiver (bottom), in accordance with an embodiment of the invention;

[0014] FIG. **5** schematically illustrates a spherical receiver on an absorber tube and a heat distributor sleeve below the receiver, in accordance with an embodiment of the invention;

[0015] FIG. **6** schematically illustrates a concave receiver on an absorber tube and a heat distributor sleeve downstream of the receiver, in accordance with an embodiment of the invention;

[0016] FIG. **7** shows values for efficiency of solar absorption calculated as a function of temperature for various values of emissivity ("E") and concentration ratios ("c"), in accordance with an embodiment of the invention; and

[0017] FIG. **8** schematically illustrates a receiver, in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] While various embodiments of the invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions may occur to those skilled in the art without departing from the invention. It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention.

[0019] A parabolic trough is a type of solar thermal energy collector. It may be constructed as a long parabolic mirror (usually coated silver or polished aluminum) with an evacuated or Dewar tube running its length at the focal point. Sunlight is reflected by the mirror and concentrated on the tube. The trough is usually aligned on a north-south axis, and rotated to track the sun as it moves across the sky each day.

[0020] There are problems and limitations associated with current parabolic troughs and systems. For example, manufacturing and maintenance costs may be high for vacuum tube receivers. As another example, the solar concentration ratio in troughs is typically limited to values of 40 to 90, which may place an upper limit on the operating temperature of such troughs. In addition, current troughs may have high optical intercept losses due to inefficient absorption of solar radiation arriving at shallow angles due to latitude and yearly variation in the sun's elevation angle. Intercept losses may be lower when the solar radiation falls closer to an axis normal to a plane having the receiver. Intercept losses may be higher when the radiation striking the receiver is at a more glancing angle which is when the radiation is farther from the normal to the receiver. In addition, troughs experience significant cosine losses.

[0021] A parabolic trough concentrates reflected solar radiation along a line at the trough's focus. This may impose serious constraints on the optical components. For example, since light is being absorbed all along the line, the design of the receiver must allow light to pass through for absorption while at the same time minimizing heat losses. This leads to a evacuated tube design with a transparent glass outer tube. However, while the vacuum is efficient at eliminating conduction and convection losses, it does not stop radiative losses which scale as T^4 (with 'T' being temperature) and become substantial at higher temperatures. The seals required for these parabolic trough-based receivers typically are designed to compensate for differential expansion of glass and metal, and special design features are typically used to compensate for hydrogen permeation. This leads to considerable complexity, which may lead to increases in startup and maintenance costs.

[0022] The term "concentration ratio", as used herein, refers to the ratio of the area of the reflector in a plane perpendicular to its focal axis, to the area of the receiver on which concentrated sunlight falls.

[0023] The term "reflector", as used herein, refers to any surface for collecting and directing solar radiation. A reflector may direct solar radiation toward a focal point of a reflector. In some cases, a reflector may be a trough, such as a concave or parabolic trough.

[0024] The term "solar radiation", as used herein, refers to light from the sun or any other star. Solar radiation may be provided directly from the sun or star or indirectly, such as via scattering or reflection by way of the moon or other celestial object, such as a planet. Solar radiation includes photons.

[0025] The term "heat storage material" or "energy storage material", as used herein, refers to any material that is configured to store (or retain) and release energy. Upon absorbing energy, a temperature of a heat transfer storage material my increase. Upon releasing energy, the temperature of the heat transfer storage material may decrease. A heat storage material (also "heat transfer storage material" and "energy transfer storage material" herein) may be for storing and/or transferring energy.

[0026] The term "receiver", as used herein, refers to any device for accepting solar radiation from a reflector and transmitting energy from received solar radiation to a heat transfer storage material.

[0027] The term "heat transfer tube", as used herein, refers to any device for conveying or flowing a heat transfer storage material across one or more reflectors. A heat transfer tube may be referred to as an "absorber tube".

[0028] The term "solar collector", as used herein, refers to a device or system comprising one or more reflectors, one or more receivers and one or more absorber tubes.

[0029] The terms "north", "south", "east" and "west", as used herein, refer to directional vectors. The north and south vectors are anti-parallel to one another, and the east and west are anti-parallel to one another. The north and south vectors are orthogonal to the east and west vectors. The north and south vectors are situated along an axis that is orthogonal to an axis having the east and west vectors. Where such terms are used, it will be appreciated that such terms are merely illustrative and need not designate the physical orientation of a device or object with respect to the Earth's geographic or magnetic poles.

[0030] The term "in-line", as used herein, refers to two or more or three or more objects, such as reflectors, but are disposed along a line connecting the two or more objects.

[0031] Embodiments of the invention provide troughs for collecting and concentrating solar radiation at various glancing angles, which advantageously reduces (or minimizes) losses, such as intercept losses, cosine losses, thereby leading to improved collector and thermal energy collector efficiency. Embodiments of the invention provide solar collectors having multi-axis solar concentrators for collecting and concentrating solar radiation onto a heat transfer tube (also "absorber tube" herein). The heat transfer tube may include a heat transfer medium, such as an oil or organic material or an inorganic material such as molten salt, or a gas such as steam, that absorbs heat transferred from the receiver. The receiver receives concentrated sunlight (photons) and absorbs the energy contained into heat. Sunlight incident on the heat transfer tube increases the temperature of the fluid. The heat transfer fluid may then used to heat steam in a turbine generator.

[0032] Thermal energy collectors provided herein may eliminate the need for vacuum tube-based receivers and provided for higher efficiencies of energy collection at reduced cost relative to current systems. One area of application for the present invention is utility scale solar thermal power generation.

Systems for Generating Power

[0033] In an aspect of the invention, a system for collecting thermal radiation comprises an array of reflectors for focusing solar radiation at discrete points along an absorber tube, the absorber tube for conveying a thermal energy transfer medium. In some situations, a portion of the heat transfer tube along the reflectors is substantially straight. Solar radiation is collected and focused by the array of reflectors onto receivers disposed along the heat transfer tube. Solar radiation heats the thermal energy transfer medium (Heat transfer storage fluid), which could subsequently be used to generate steam in a heat exchanger. Steam could then be used to drive a turbine to generate electricity, generating cooled water from steam. Cooled water is returned to the heat exchanger for generating steam. Heat absorbed by the heat transfer storage fluid or the steam generated could also be used in other applications.

[0034] FIG. **1** shows a system **100** for generating electricity, in accordance with an embodiment of the invention. The system includes an array of solar collectors **105** having heat transfer tubes in fluid communication with a reheater **110**, turbine **115**, condenser **120**, economizer **125**, vaporizer **130**, superheater **135** and heat exchanger **140**.

[0035] A thermal energy transfer medium (also "heat storage material" herein) in the heat transfer tubes of the solar collectors **105** is heated by solar radiation, as directed by reflectors, and directed (along the direction of the arrow) to the superheater **135** and reheater **110**, where heat from the thermal energy transfer medium is used to generate heated water (or steam) from liquid water. Steam is used to generate electricity in the turbine **115**. Cooled thermal energy transfer medium is returned to the solar collectors for reheating. Cooled (or liquid) water is subsequently returned to the superheater **135** and the reheater **110** to generate steam from the heated thermal energy transfer medium.

[0036] The superheater **135** may be in fluid communication with a vaporizer **130** and economizer **125**. The vaporizer **130** may generate steam from heater water; the economizer **125** may preheat liquid water prior to vaporization in the vaporizer **130**.

Thermal Collectors

[0037] In an aspect of the invention, a solar collector comprises an heat transfer tube having a thermal energy storage material, a receiver disposed along the heat transfer tube, the receiver for directing solar radiation to the thermal energy storage material, and a reflector supported by a support structure, the reflector for focusing solar radiation at the receiver, the reflector for collecting and focusing solar radiation along dual axes.

[0038] In some situations the reflector may be part of a linear array of reflectors (also "reflector units" herein). The reflector array may be a linear point focus array.

[0039] The heat transfer tube is configured to store and flow (or direct) the thermal energy storage material through one or more receivers in thermal communication with the thermal energy storage material. In some cases, the heat transfer tube is in fluid communication with a heat exchanger, which is used to heat a working fluid (e.g., water) for generating power with the aid of a turbine.

[0040] The thermal energy storage material may be directed through the heat transfer tube with the aid of a pump in fluid communication with the heat transfer tube. The pump may be a positive displacement pump or a negative displacement pump. In some situations, the pump is a mechanical pump.

[0041] The support structure may be formed of one or more metals and a composite material. In some cases, the support structure may be formed of stainless steel or aluminum. The support structure may provide structure support to the solar collector (including reflector). In addition, the support structure may enable the reflector to pivot about multiple axes.

[0042] The reflector focuses light onto a discrete region of the heat transfer tube. The discrete region is disposed at the receiver of the solar collector. The heat transfer tube may be formed of a transparent material (e.g., vacuum tube) at the discrete points; the remainder of the heat transfer tube need not be formed of the transparent material. For instance, portions of the heat transfer tube that are not at the discrete points may be formed of an optically opaque material. This advantageously provides for savings in materials costs and/or improvements in efficiency.

[0043] The thermal energy storage material may include a molten salt, such as, for example, fluoride salt, potassium salt, or sodium salt. In some cases, the thermal energy storage material may include one or more of sodium nitrate and potassium nitrate. For instance, the thermal energy storage material may include sodium nitrate and potassium nitrate. The thermal energy storage material may have a sodium nitrate composition of at least about 40%, or 45%, or 50%, or 55%, or 60%, or 65%, or 70%, or 75%, or 80%, or 85%, or 90%, or 95%, with the balance potassium nitrate. As one example, the thermal energy storage material may include sodium nitrate and potassium nitrate in a 3-to-2 ratio (i.e., 60% sodium nitrate and 40% potassium nitrate). In some situations, the thermal energy storage material may include an oil. In other situations, the thermal energy storage material may include steam or another gas.

[0044] Solar collectors provided herein eliminate the need for vacuum tubes, which may be required for at least some current solar collectors. As such, in some situations cheaper and rugged insulation materials may be used, thereby reducing installation, handling and maintenance issues.

[0045] FIG. **2** shows an array of solar collectors **200**, in accordance with an embodiment of the invention. The array **200** includes individual solar collectors **205**, **210**, **215**, **220** and **225**. Each of the collectors **205**, **210**, **215**, **220** and **225** includes a reflector having at its focal point a receiver. For instance, the collector **205** has a reflector **230** having at its focal point a receiver **235**.

[0046] The solar collectors **205**, **210**, **215**, **220** and **225** are configured to direct solar radiation toward receivers **235**, **240**, **245**, **250** and **255** disposed along an heat transfer tube **260**. The heat transfer tube **260** is for housing and directing a thermal energy transfer material. Each of the receivers may be located at a focal point of a reflector. For instance, the receiver **235** may be located at the focal point of the reflector **230**.

[0047] The collector **200** may include a first support structure **265***a* and a second support structure **265***b* for supporting the collectors and for rotating the collectors along dual axes. The support structures **265***a* and **265***b* may be for rotating the reflectors individually along a first axis (also called north-south axis herein) about the first axis pivot points, and the support structures **265***a* and **265***b* may be for rotating the reflectors collectively along a second axis (also called east-west axis herein). The north-south axis pivot points may be at the same height as the focal point of each of the reflectors. It will be appreciated that the designation of such axes is selected for illustrative purposes only and is not to limit other potential orientations of the support structures **265***a* and **265***b*.

[0048] Each of the reflectors of the collector **200** may be rotated along or parallel to a first axis perpendicular to the heat transfer tube **260** and along a second axis orthogonal to the first axis and parallel to the heat transfer tube. Rotation along the first axis may be independent from rotation along the second axis, and vice versa. The first and second support structures **265***a* and **265***b* may be connected to one another with the aid of one or more support structures, such as one or more U-shaped support structures that pass below each of the reflectors of the collectors **205**, **210**, **215**, **220** and **225**. The first and second support structures **265***a* and **265***b* may be for moving (or rotating) the reflectors of the solar collectors **205**, **210**, **215**, **220** and **225** along a second axis. This may be accomplished with the aid of one or more motors or devices operatively coupled to the support structures **265***a* and **265***b*. In some embodiments, the first support structure **265***a* and the second support structure **265***b* may be for collectively moving (i.e., in unison) the solar collectors **205**, **210**, **215**, **220** and **225** along the second axis. A motor or other device adjacent the collector **200** may be provided for rotating the reflector **230** (and other reflectors) along or parallel to the first axis. Such motor or other device may be operatively coupled to another support structure at the periphery of the collector **200**.

[0049] With continued reference to FIG. **2**, the heat transfer tube **260** includes a plurality of isothermal heat distributor sleeves adjacent each of the receivers **235**, **240**, **245**, **250** and **255**. The isothermal heat distributor is disposed between each of the receivers **235**, **240**, **245**, **250** and **255** and the heat transfer tube **260**. The isothermal heat distributor may be oriented along the heat transfer tube **260**. The heat transfer tube **260**, at locations between the receivers **235**, **240**, **245**, **250** and **255**, may be formed of an opaque material. The isothermal heat distributor sleeves may be formed of high thermal conductivity materials or devices, such as heat pipe (s). The isothermal heat distributor sleeves are used to distribute heat absorbed by the receiver over a larger area of the absorber tube in order to reduce or optimize the heat flux received by the thermal transport and/or storage material in the heat transfer tube. Opaque insulation may be used along a major portion of the heat transfer tube, which may enable a reduction in conductive, convective and radiative losses. An opaque insulating material may be used for at least a portion of the absorber.

[0050] In some situations, portions of the heat transfer tube between the plurality of receivers are formed of multiple layers of pipe with the innermost pipe carrying the thermal energy storage material. The multiple layers of pipe may includes gases, such as hydrogen or helium, or a vacuum in between one layer and another layer. In some cases, the multiple layers of pipe may include bellows at intervals to compensate for differential expansion of the layers of pipe which are at different temperatures.

[0051] Reflectors provided herein, such as the reflector **230** of FIG. **2**, may be concave and configured to rotate along dual axes along a plane orthogonal to an axis directed through the center and focal point of the reflector. That is, reflectors may be configured to rotate (or pivot) along north-south and east-west axes, or a combination of such axes, such as north-east/south west and north-west/south-east. For example, a reflector may pivot about dual axes, such as north-south and east west axes that are orthogonal to one another. This may enable a reflector to collect solar radiation from the sun at various points in the sky through the year, thereby increasing the time period for use of such reflectors. This also obviates the need to move or shift reflectors throughout the year, as they may be pivoted to collect solar radiation as the position of the sun changes throughout the year.

[0052] Reflectors provided herein, such as the reflector **230** of FIG. **2**, may have a curvature between about 15° and 270° along a north-south axis and a curvature between about 15° and 270° along an east-west axis. The reflector **230** may be symmetrical along its north-south or east-west axes.

[0053] Reflectors may be formed of an optically reflective material, such as a reflective metal or a composite material having reflective properties. In some situations, a reflector may include one or more of a metallic material and a polymeric material. For instance, a reflector may include silver and a polymeric material. In other situations, a reflector may be formed of glass with a reflective coating, such as silver.

[0054] Reflectors may be disposed a short distance from one another, such as less than 1 foot "ft"), or 2 ft, or 3 ft, or 4 ft, or 5 ft, or 6 ft, or 7 ft, or 8 ft, or 9 ft, or 10 ft from one another, thereby enabling for a reduction in materials costs and a maximization of thermal efficiency. Center-to-center distances between adjacent reflectors may be at least about 0.5 feet ("ft"), or 1 ft, or 2 ft, or 3 ft, or 4 ft, or 5 ft, or 6 ft, or 7 ft, or 8 ft, or 9 ft, or 10 ft, or 20 ft, of 30 ft, or 40 ft, or 50 ft, or 60 ft, or 70 ft.

[0055] Heat collection regions of an heat transfer tube may require less insulation compared to traditional dish-based designs. In addition, land may be used more efficiently. In an embodiment, reflector units may have a square or rectangular top-down profile. In another embodiment, a top-down profile geometry may be chosen to increase the reflective surface area covered. For example, reflector units may be provided in a circular, triangular, square, rectangular, pentagonal, or hexagonal top-down profile.

[0056] Solar collectors provided herein may operate at higher temperatures in comparison to other solar collectors. For instance, solar collectors may operate at a temperature of 200° C. or more, or 300° C. or more, or 400 ° C. or more, or 500° C. or more, or 600° C. or more, or 700° C. or more, or 800° C. or more. At such temperatures, the thermal energy transfer and/or storage material may be a molten salt or other fluid or gas (such as air or steam).

[0057] The reflector may track the sun along two axes throughout the year, thereby reducing intercept losses. Reflectors provided herein may pivot about two axes, thereby enabling reflectors to collect and focus solar radiation along multiple angles.

[0058] FIG. **3** shows a solar collector **300** having an array of reflectors **305**, in accordance with an embodiment of the invention. Each reflector in the array **305** is configured to direct solar radiation to a receiver **310** disposed at a focal point of the reflector.

[0059] In some embodiments, the rotation of the reflector is decoupled from the receiver in the north-south axis (or east-west axis). While the dish rotates along the north-south axis during the day and throughout the year, the receiver does not move along the north-south axis. In other embodiments, the rotation of the reflector is decoupled from the receiver in the north-south as well as the east-west axes, and in such cases the heat transfer pipe and receivers could be stationary while the reflectors would move along dual axes.

Receivers

[0060] Solar collectors and systems provided herein include receivers for transmitting energy from solar radiation to a thermal energy storage material, which may subsequently be used to generate an energized working fluid (e.g., steam) to drive a turbine for power generation.

[0061] In some instances, receivers may be spherical or concave. FIG. **4** (top) shows a concave receiver (top) and spherical receiver (bottom), each configured to direct solar radiation (and energy) to a thermal energy storage material. The spherical receiver may be able to accept solar radiation from a wide range of angles than the concave receiver. In some cases, with $\square_{NS}$ representing the angle between a reflector at the focal point in the north-south direction, the concave receiver may allow $\square_{NS}$ less than about 90° and the spherical receiver may allow $\square_{NS}$ less than about 150°.

[0062] In some cases, solar collectors may include turbulators, which disturb the flow of a thermal energy storage material and mixing the heated fluid inside the heat transfer tubes (also "heat transfer fluid pipes", or "HTF pipes", herein). Examples of turbulators include twisted tape turbulators, brock turbulators, wire coil turbulators etc.

[0063] FIG. **5** shows a spherical receiver **505** mounted on a heat transfer tube **510**, and a heat distributor sleeve **515** below the receiver **505**. In some situations, the sleeve **515** may extend upstream and/or downstream from the receiver **505**. For instance, the sleeve **515** may be on both sides of the receiver **505**. In some implementations, a concave receiver may be used, as shown in FIG. **6**. The sleeve **515** is disposed between the receive r **505** and the heat transfer tube **510**.

[0064] In one embodiment, the receiver may be designed to be an effective cavity into which light that has been focused from the dish enters and undergoes multiple reflections until it is absorbed into the inner or outer surface of the receiver. Both inner and outer surfaces of the receiver may be in good thermal contact with the heat transfer fluid. Since high concentration ratios may be achieved in various embodiments, the concentration ratio may be adjusted to achieve a desired efficiency based on the emissivity of the materials in the cavity and the desired final temperature (as shown in FIG. **7**). The plots shown in FIG. **7** are calculated values for the efficiency of solar absorption as a function of temperature for various values of emissivity and concentration ratios. In one embodiment these calculations can be used to determine the concentration ratio required given other operational parameters such as emissivity to achieve a particular efficiency at a given temperature. For example in one embodiment as the emissivity of the inner cavity surface changes (due to for example oxidation), the concentration ratio can be changed to maintain a particular efficiency at a given temperature. In another embodiment as the emissivity of the inner cavity surface changes, the temperature can be changed (by for example changing the fluid flow rate) to maintain a particular efficiency given a particular concentration ratio. Various receiver cavity geometries are contemplated in accordance with the inventive concept of the present invention.

[0065] FIG. **8** schematically illustrates an alternative receiver **800** for use with solar collectors. The receiver **800** may be used with any of the reflectors provided herein. The receiver **800** includes an opening **805** for accepting solar radiation (h□) from a reflector. Solar radiation, or flux of energy, heats a heat transfer medium in the receiver **800**. In the illustrated embodiment, the heat transfer medium in the receiver **800** is a sodium pool. Energy from the sodium pool is transferred to engine heater tubes having an engine working fluid, which is heated by the transferred energy. This drives pistons in the generator to produce power (electricity).

[0066] In some cases, the receiver **800** may obviate the need to have an absorber tube as solar radiation is used to generate power with the aid of the turbine directly attached to the receiver. However, in other cases, the receiver **800** may be modified to be in thermal communication with an absorber tube such that solar radiation heats a thermal transfer medium in both the absorber tube (as shown in FIG. **2**, for example) and the receiver (as shown in FIG. **8**), thus providing heat for heating a working fluid that may be used to generate power using a turbine downstream from the absorber tube.

Operation

[0067] In another aspect of the invention, methods for operating a solar collector are provided. In some implementations, a heat storage material (also "heat transport fluid" herein) enters one end of a linear array of reflector receiver units. For each reflector receiver unit in the array solar radiation is concentrated by the reflector into the receiver unit. At least a portion of the thermal radiation absorbed by the receiver unit is transferred to the heat transport fluid which is in thermal contact with the receiver unit. In one embodiment as the heat transport fluid passes through successive receiver units, parameters describing its state, such as temperature or pressure, change. For example, in an embodiment, the fluid enters the array of reflectors receiver units through the absorber tube at an initial temperature that increases in steps at each unit until the fluid exits the array at a final temperature that is above the initial temperature. In one embodiment, the initial temperature is approximately 200° C. and the final temperature is approximately 400° C. The invention is in no way limited to particular values of initial and final temperatures and can include, for example, final temperatures in the range of 300° C. to 900° C.

EXAMPLE 1

[0068] As an illustrative example, an increase of about 1% in solar to electric efficiency (for example, from 20% to 21%) results in an increase of (21-20)/20=5% in the electricity produced by a plant for generating power with the aid of energy provided by solar collectors. Assuming that the total solar to electric efficiency of a trough (or solar collector)-based power plant is 20%, improvements in efficiency that reduce intercept losses and employ molten salts, as described above, may result in a final efficiency of 0.2*(1/0.9)*(0.4/0.35)=0.254, or about 25%. Electricity production may be increased by 25% relative to a standard trough plant. This effectively reduces the cost of generating power by the plant by about a quarter.

EXAMPLE 2

[0069] An array of solar collectors may include five solar collectors adjacent one another, as illustrated in

[0070] FIG. **2**. The solar collectors include reflectors, an absorber tube running down array of reflectors, and receivers at focal points of the reflectors. Solar energy incident on the reflectors is reflected to the receivers. The receivers are spherical receivers, as illustrated in FIG. **5**. A thermal energy transfer material including sodium nitrate and potassium nitrate (in a 3-to-2 ratio) is successively heated with the aid of the reflectors from an initial temperature of about 200° C. to a final temperature of about 600° C. The thermal energy storage material is then used to generate steam, which is subsequently used to generate power in a turbine.

[0071] Systems and methods provided herein may be combined with or modified by other systems and methods, such as, for example, systems and/or methods provided by U.S. Patent Publication No. 2011/0048405 to Koetter et al. ("PARABOLIC TROUGH COLLECTOR") and U.S. Pat. No. 7,240,675 to Eickhoff ("PARABOLIC TROUGH COLLECTOR"), which are entirely incorporated herein by reference.

[0072] It should be understood from the foregoing that, while particular implementations have been illustrated and described, various modifications can be made thereto and are contemplated herein. It is also not intended that the invention be limited by the specific examples provided within the specification. While the invention has been described with reference to the aforementioned specification, the descriptions and illustrations of embodiments of the invention herein are not meant to be construed in a limiting sense. Furthermore, it shall be understood that all aspects of the invention are not limited to the specific depictions, configurations or relative proportions set forth herein which depend upon a variety of conditions and variables. Various modifications in form and detail of the embodiments of the invention will be apparent to a person skilled in the art. It is therefore contemplated that the invention shall also cover any such modifications, variations and equivalents.

What is claimed is:

1. A solar collector, comprising:

a heat transfer tube having an energy storage material;

a receiver disposed along the heat transfer tube, the receiver for directing solar radiation to the energy storage material; and

a reflector supported by a support structure, the reflector for focusing solar radiation at the receiver, the reflector for collecting and focusing solar radiation by tracking solar radiation along dual axes.

2. The solar collector of claim **1**, wherein the support structure comprises a first support structure and a second support structure, the first and second support structures connected to one another.

3. The solar collector of claim **1**, wherein the reflector is for moving along an axis orthogonal to a plane having the first and second axes.

4. The solar collector of claim **1**, wherein each reflector is for moving along a first axis orthogonal to the heat transfer tube and along a second axis parallel to the heat transfer tube.

5. The solar collector of claim **1**, wherein the receiver is disposed substantially close to a focal point of the reflector.

6. The solar collector of claim **1**, further comprising an isothermal heat spreader disposed between the receiver and the heat transfer tube and oriented along the heat transfer tube.

7. The solar collector of claim **1**, wherein the energy storage material comprises a molten salt or oil or steam or other gas.

8. The solar collector of claim **1**, wherein the energy storage material comprises a molten salt or oil.

9. The solar collector of claim **8**, wherein the molten salt comprises one or more of sodium nitrate and potassium nitrate.

10. The solar collector of claim **9**, wherein the molten salt comprises sodium nitrate and potassium nitrate in a 3-to-2 ratio.

11. The solar collector of claim **1**, wherein the reflector comprises one or more of a metallic material and a polymeric material.

12. The solar collector of claim **11**, wherein the reflector comprises silver and the polymeric material.

13. The solar collector of claim **1**, wherein the absorber includes high temperature steel.

14. A system for collecting solar radiation, comprising:

a heat transfer tube having an energy storage material;

a plurality of receivers at discrete points along the heat transfer tube, each of the plurality of receivers for directing solar radiation to the energy storage material; and

a plurality of reflectors supported by a reflector support structure, the plurality of reflectors disposed in-line with one another, each of the plurality of reflectors for collecting and focusing solar radiation at one of the plurality of receivers, each of the plurality of reflectors for rotating along dual axes.

15. The system of claim **14**, further comprising a plurality of isothermal heat spreaders disposed along the heat transfer tube, each of the plurality of isothermal heat spreaders disposed between one of the plurality of receivers and the heat transfer tube and oriented along the heat transfer tube.

16. The system of claim **14**, wherein the heat transfer tube is substantially straight from a focal point of one reflector of the plurality of reflectors to a focal point of another reflector of the plurality of reflectors.

17. A solar collector, comprising a plurality of dual axis solar reflectors supported by a reflector support structure, each of the plurality of solar reflectors for focusing solar radiation at one of a plurality of receivers disposed along a heat transfer tube for conveying an energy storage material.

18. The system of claim **17**, wherein the heat transfer tube is runs along the reflectors in a substantially linear fashion.

19. The system of claim **17**, wherein portions of the heat transfer tube between the plurality of receivers are formed of a thermally insulating material.

20. The system of claim **19**, wherein the thermally insulating material is optically opaque.

21. The system of claim **19**, wherein the thermally insulating material is optically opaque.

22. The system of claim **17**, wherein portions of the heat transfer tube between the plurality of receivers are formed of multiple layers of pipe with the innermost pipe carrying the energy storage material.

23. The system of claim **22**, wherein the multiple layers of pipe has gases or a vacuum in between one layer and another layer.

24. The system in claim **22**, wherein the multiple layers of pipe has bellows at regular intervals to compensate for differential expansion of the layers of pipe which are at different temperatures.

* * * * *