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Winston

(54) **SOLAR THERMAL CONCENTRATOR APPARATUS, SYSTEM, AND METHOD**

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(72) Inventor: **Roland Winston**, Merced, CA (US)

(21) Appl. No.: **15/205,003**

(22) Filed: **Jul. 8, 2016**

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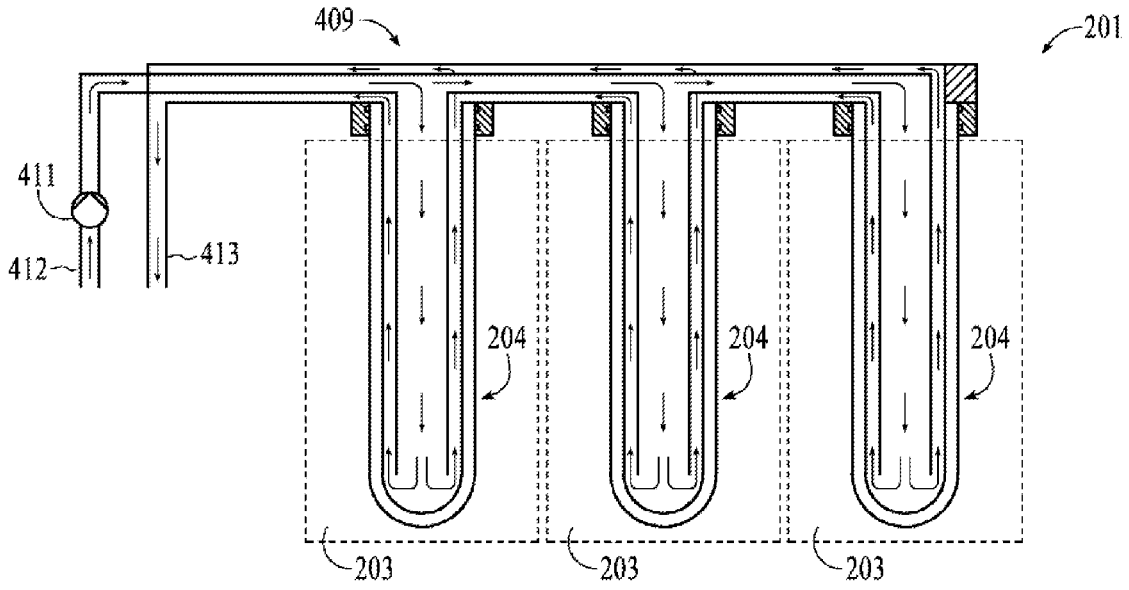
F24J 2/04	(2006.01)

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

CPC ***F24J 2/055*** (2013.01); ***F24J 2/0483*** (2013.01); ***F24J 2/12*** (2013.01); ***F24J 2/24*** (2013.01)

(57) **ABSTRACT**

An apparatus is disclosed including: a trough shaped reflector extending along a longitudinal axis and including at least one reflective surface having a shape which substantially corresponds to an edge ray involute of the absorber.



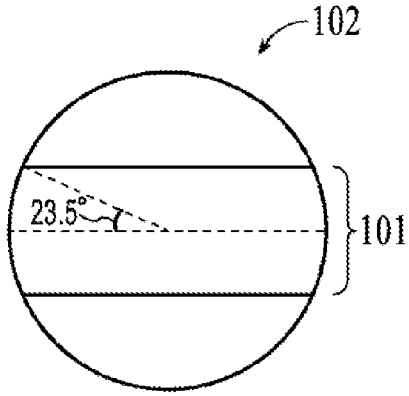


FIG. 1
(PRIOR ART)

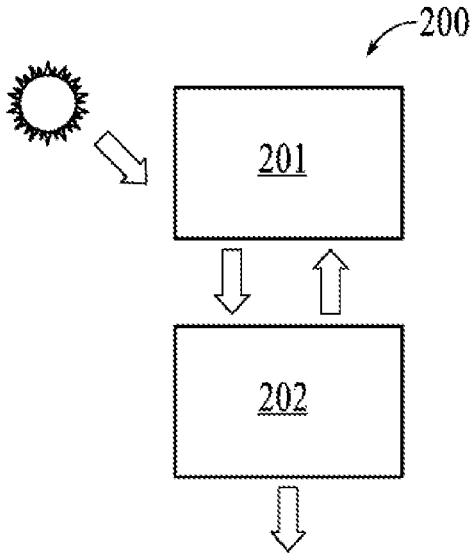


FIG. 2

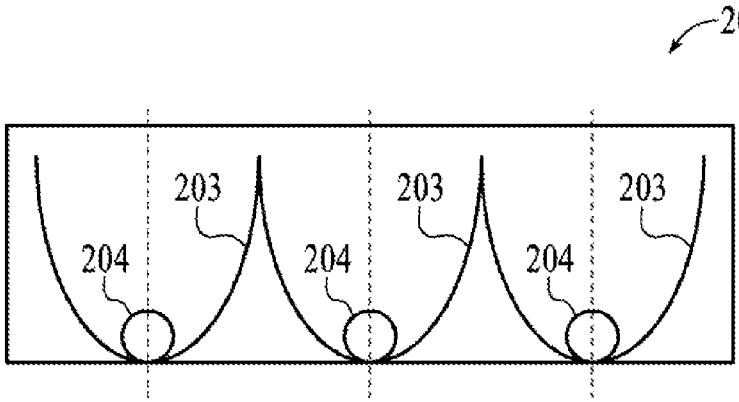

201
203
203
203
204
204
204

FIG. 3A

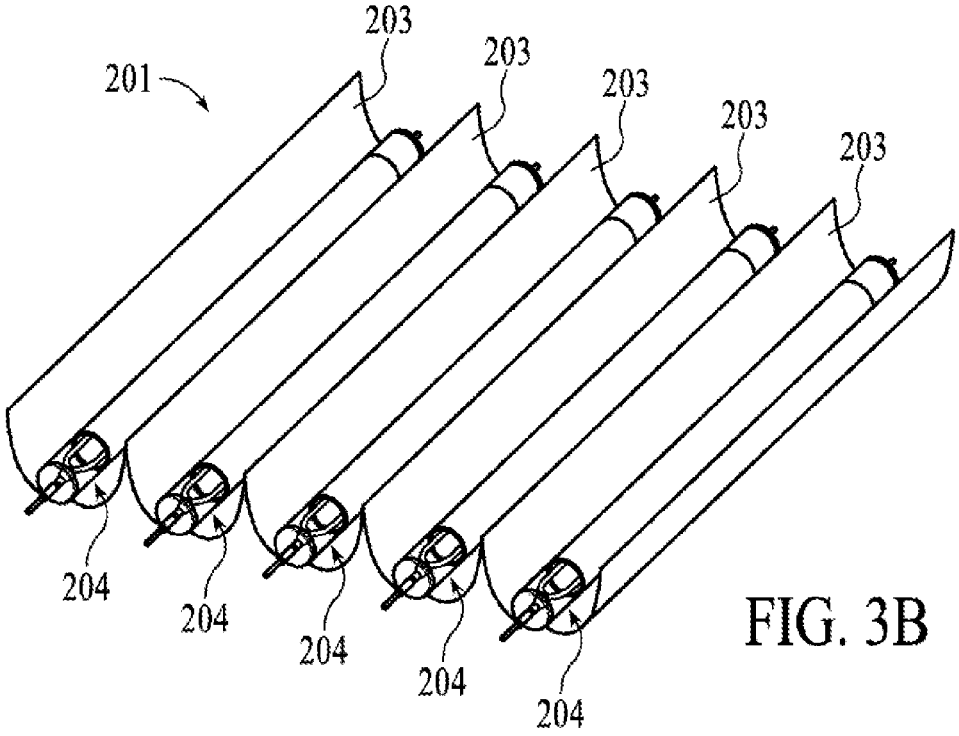

201
203
203
203
203
203
204
204
204
204
204

FIG. 3B

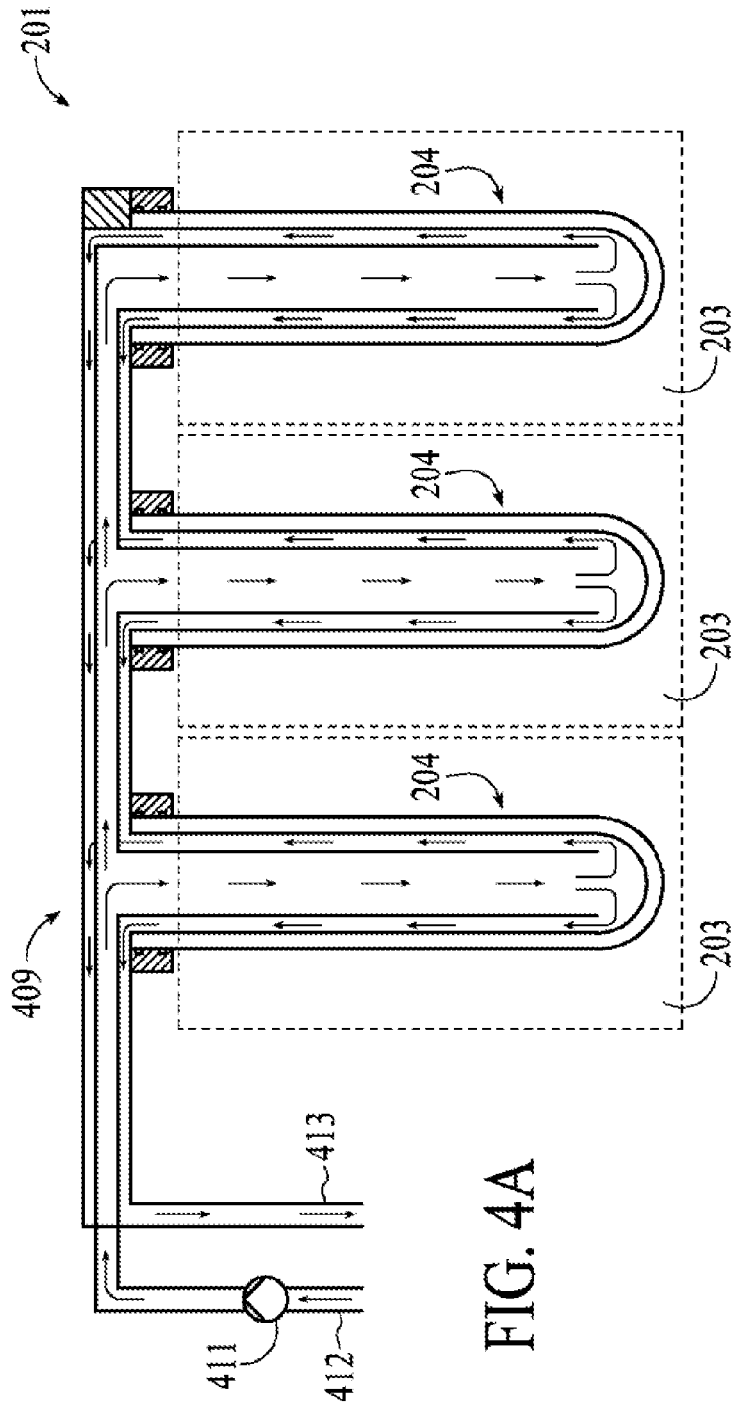

201
204
203
204
203
204
203
409
413
411
412

FIG. 4A

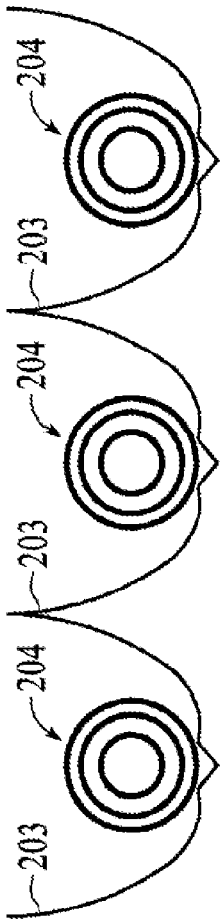

204
203
204
203
204
203

FIG. 4B

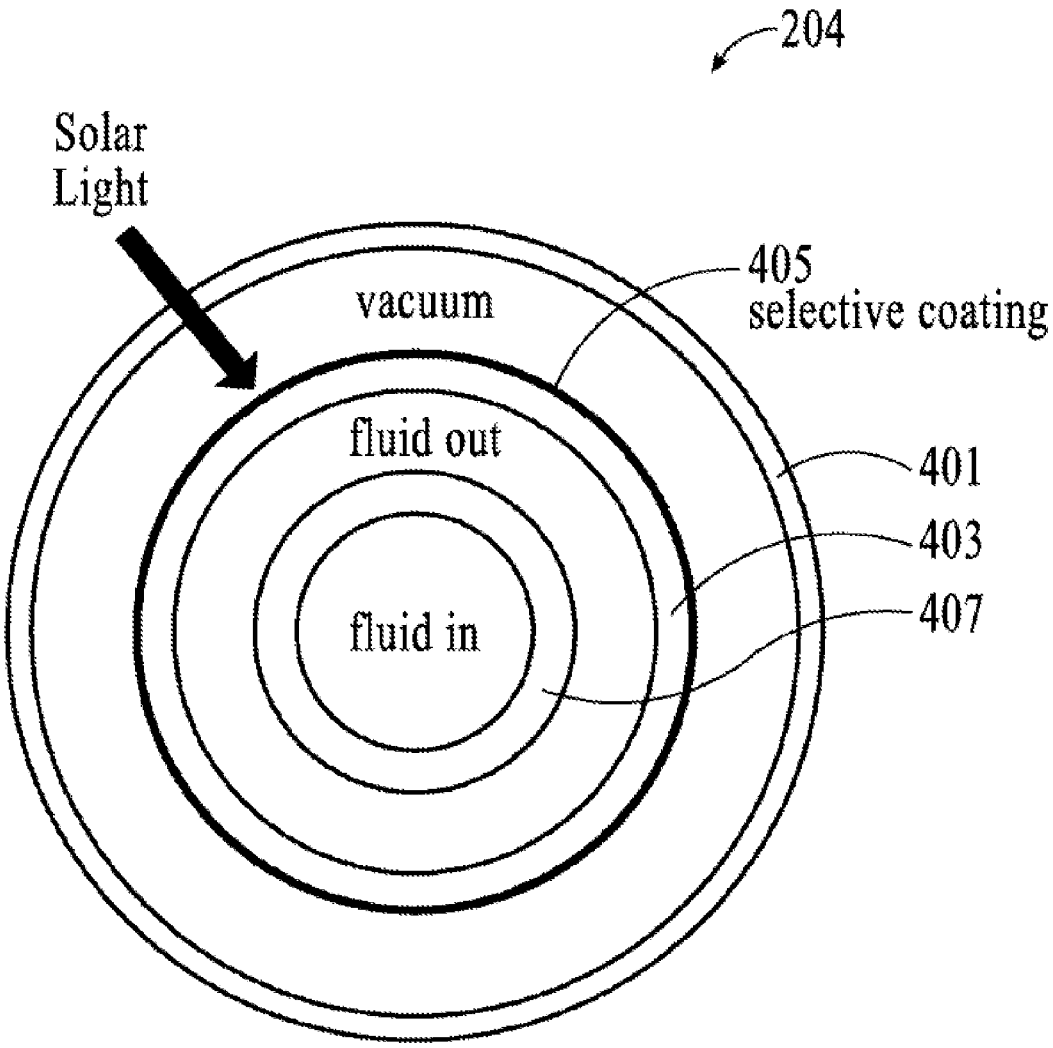

204
Solar
Light
vacuum
405
selective coating
fluid out
401
403
fluid in
407

FIG. 4C

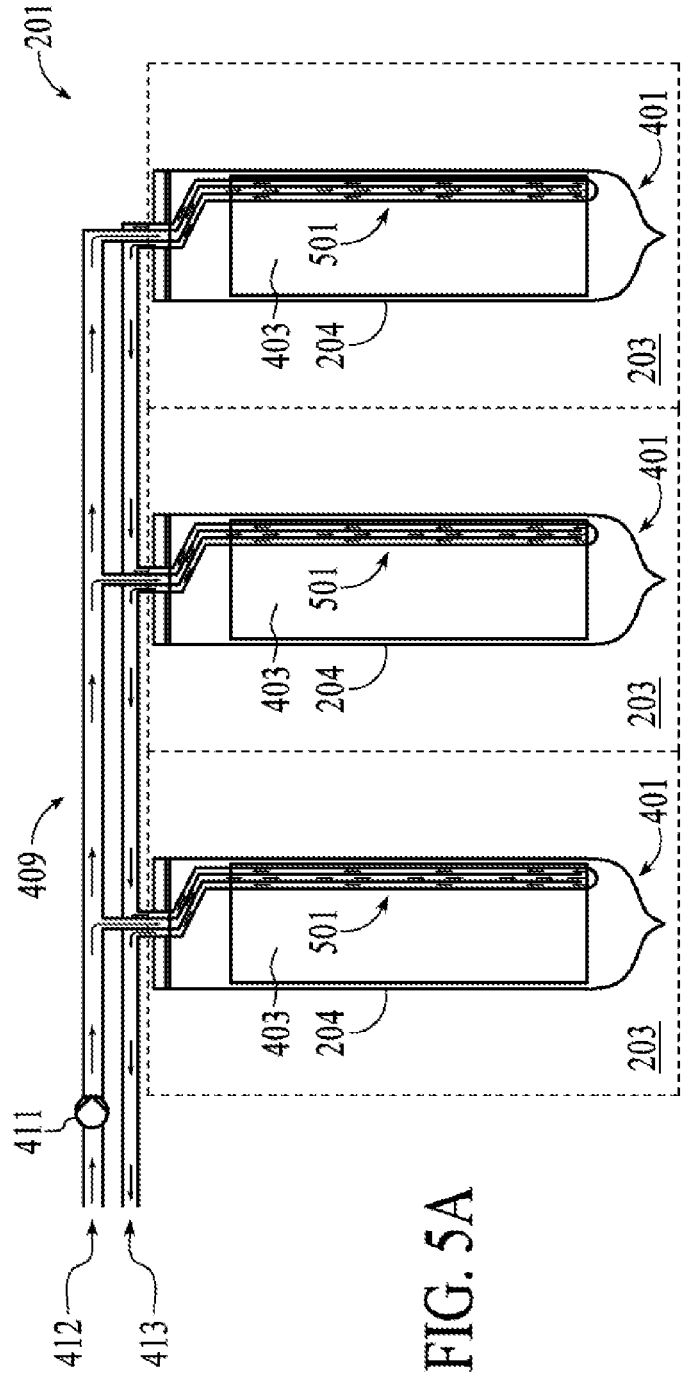


FIG. 5A

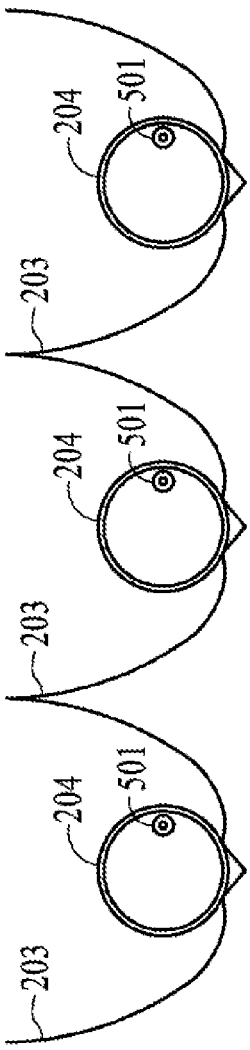


FIG. 5B

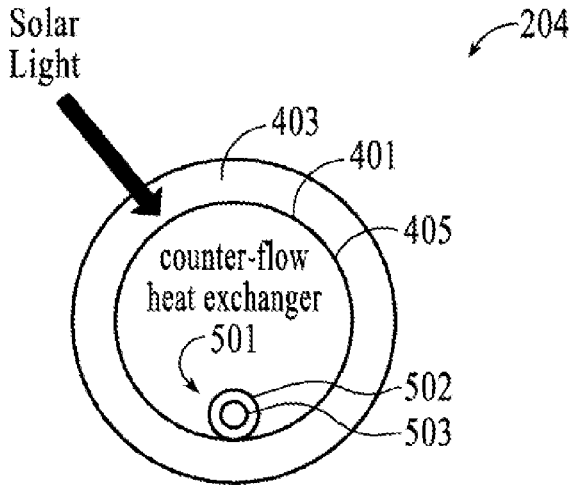

Solar
Light
204
403
401
405
counter-flow
heat exchanger
501
502
503

FIG. 5C

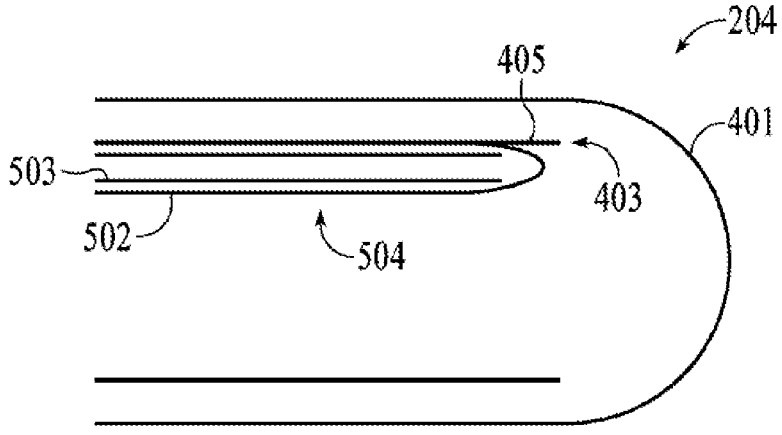

204
405
401
503
403
502
504

FIG. 5D

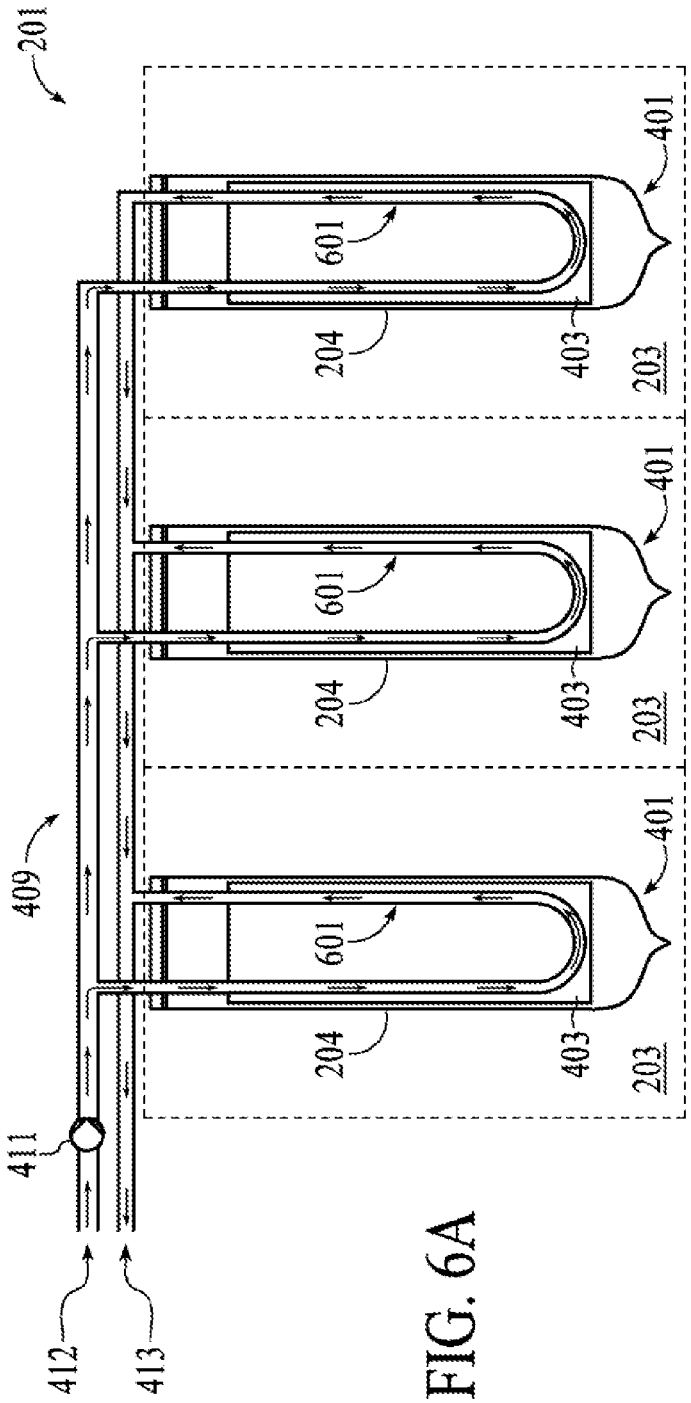


FIG. 6A

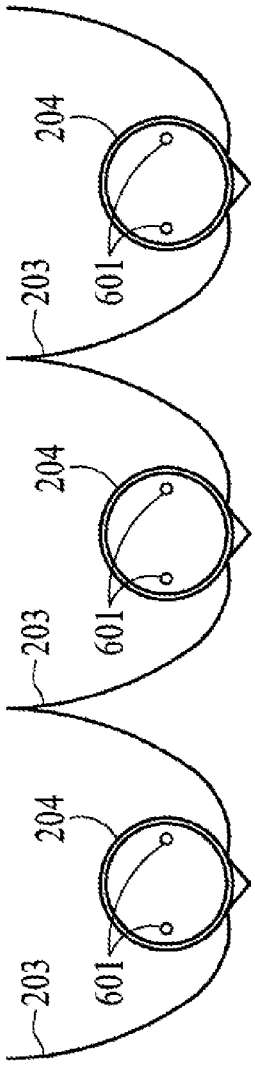


FIG. 6B

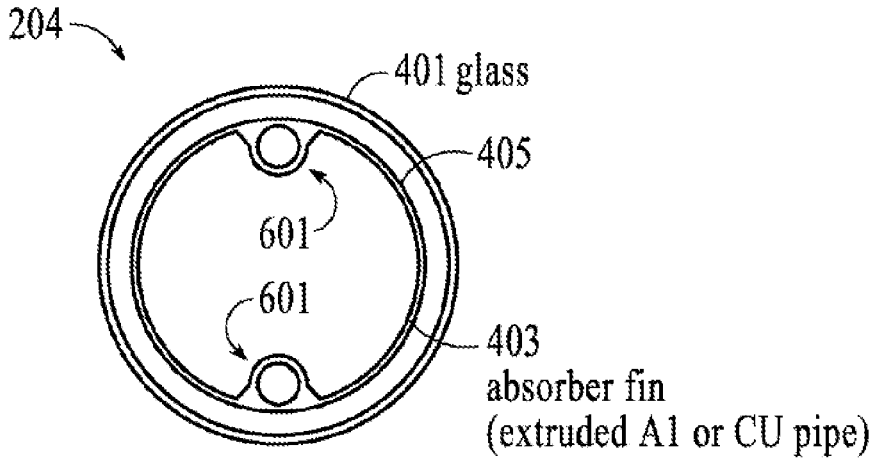

204
401 glass
405
601
601
403
absorber fin
(extruded A1 or CU pipe)

FIG. 6C

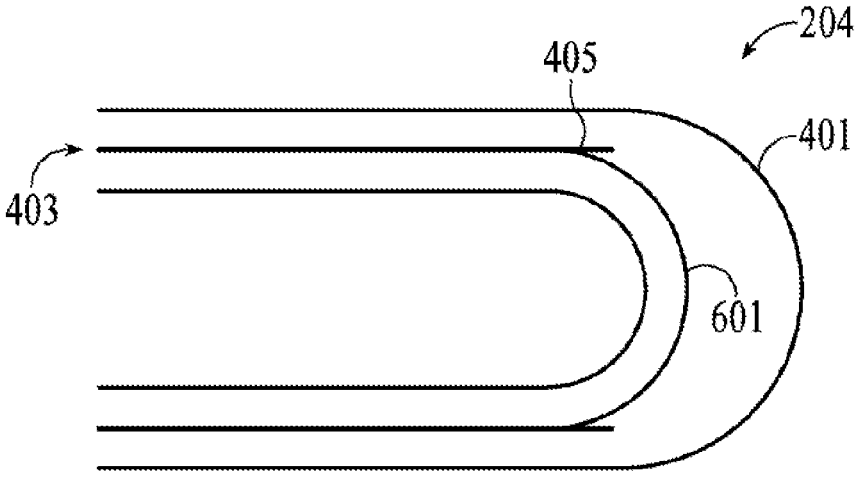

204
405
401
403
601

FIG. 6D

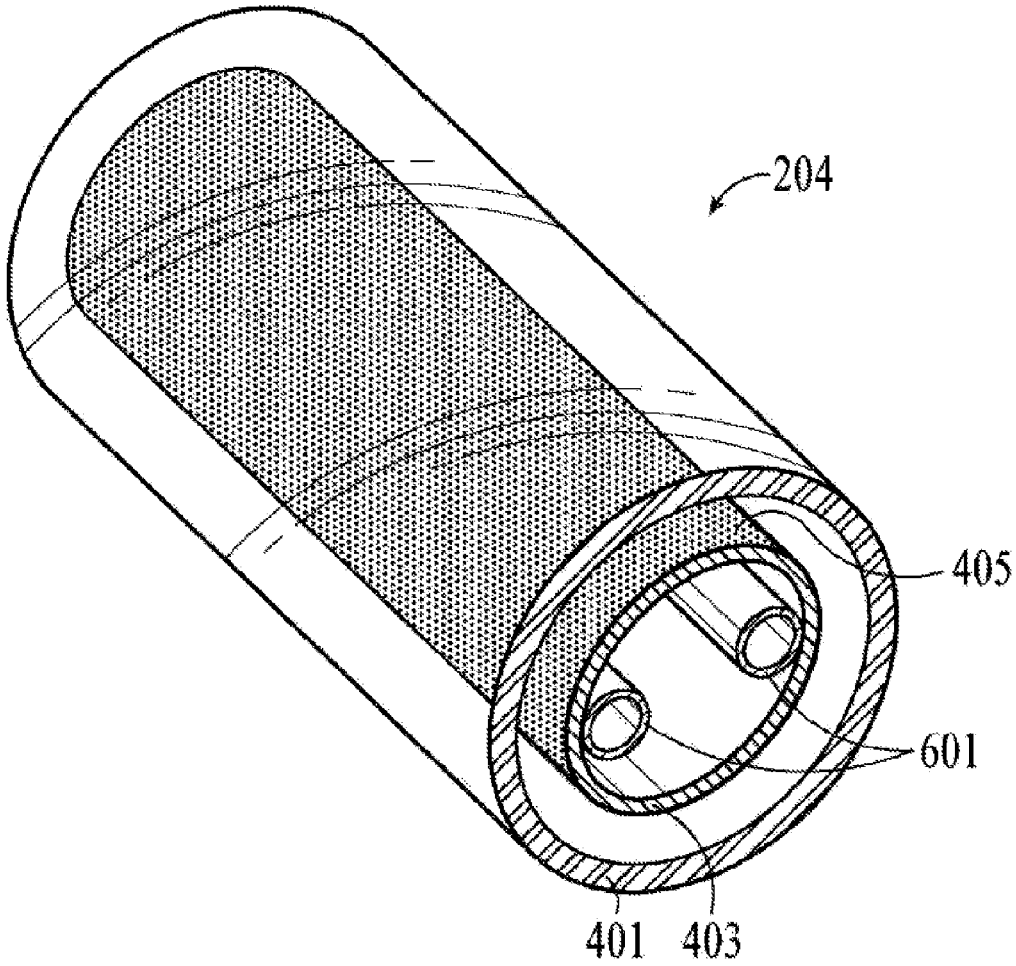


FIG. 6E

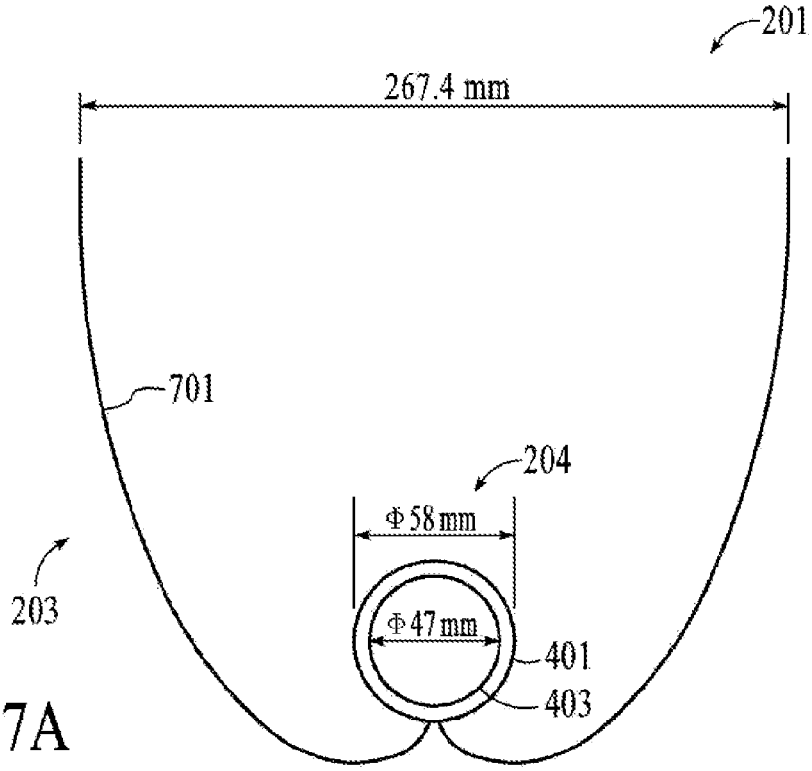

201
267.4 mm
701
204
Φ58mm
203
Φ47mm
401
403

FIG. 7A

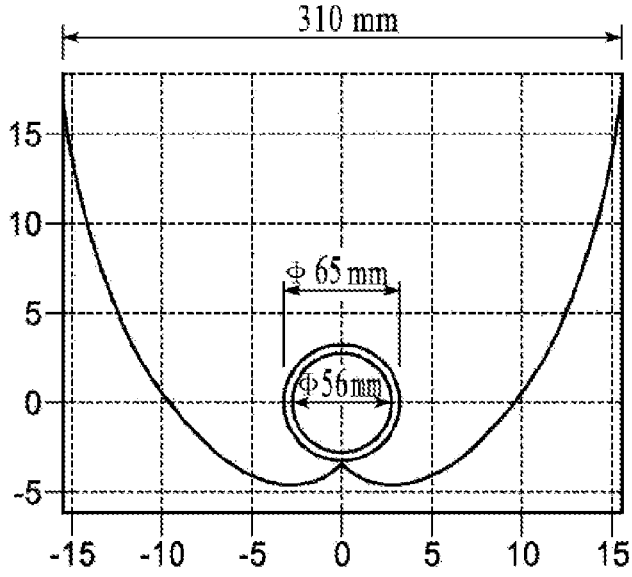

310 mm
15
10
Φ65mm
5
Φ56mm
0
-5
-15
-10
-5
0
5
10
15

FIG. 7B

FIG. 8A

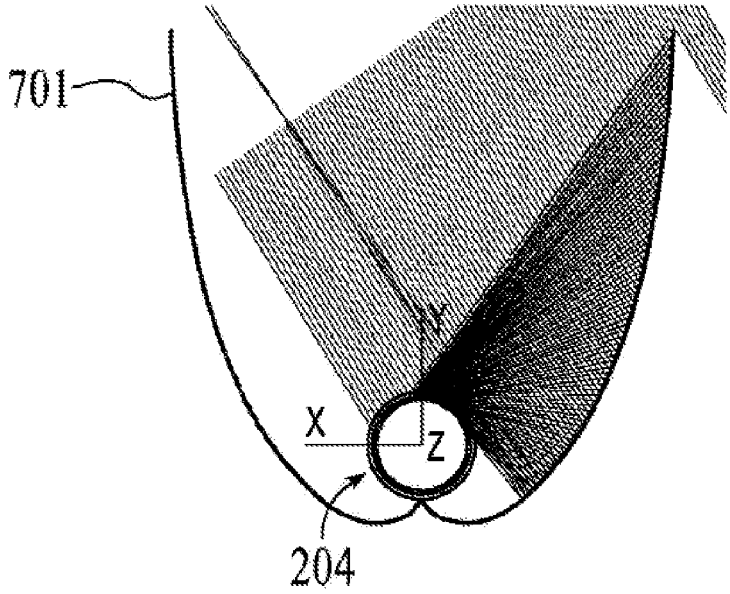


FIG. 8B

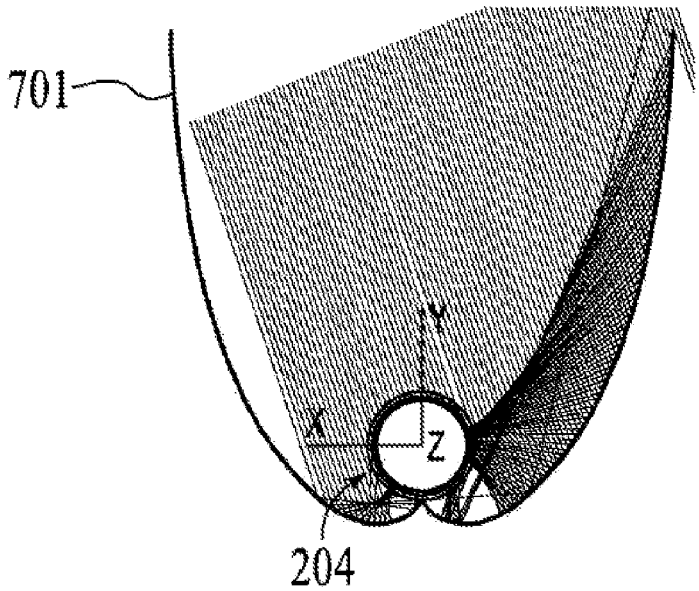


FIG. 8C

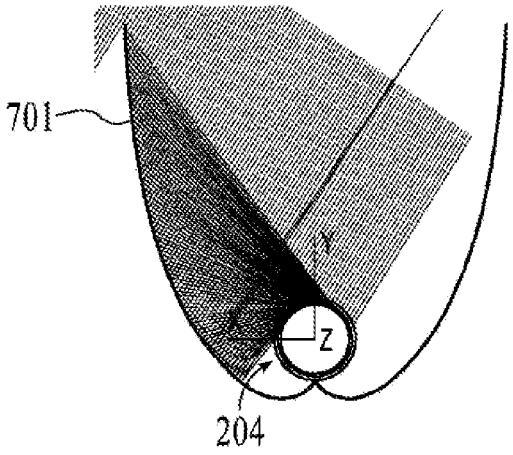


FIG. 8D

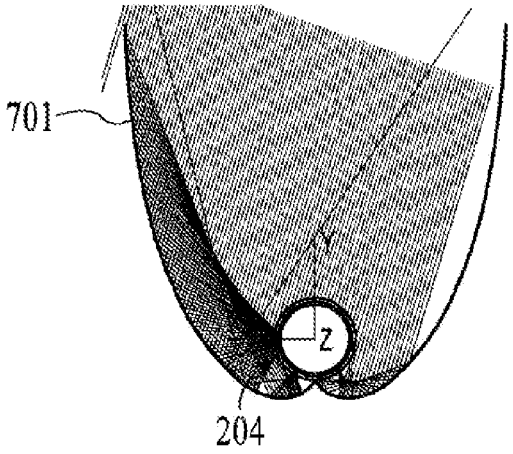
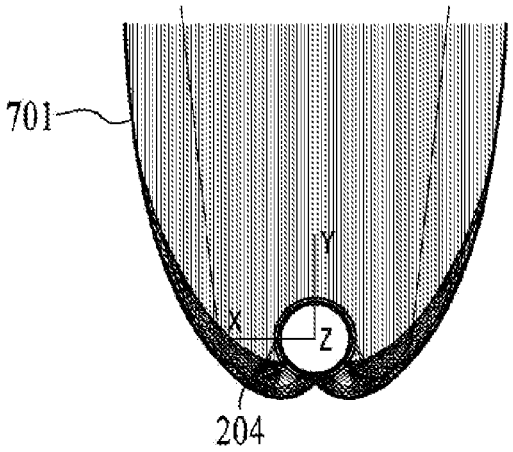


FIG. 8E



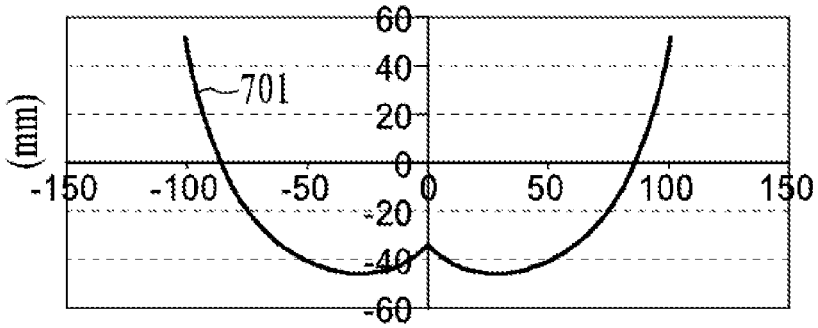

701
60
40
20
0
-20
-40
-60
(mm)
-150
-100
-50
0
50
100
150
(mm)

FIG. 9A

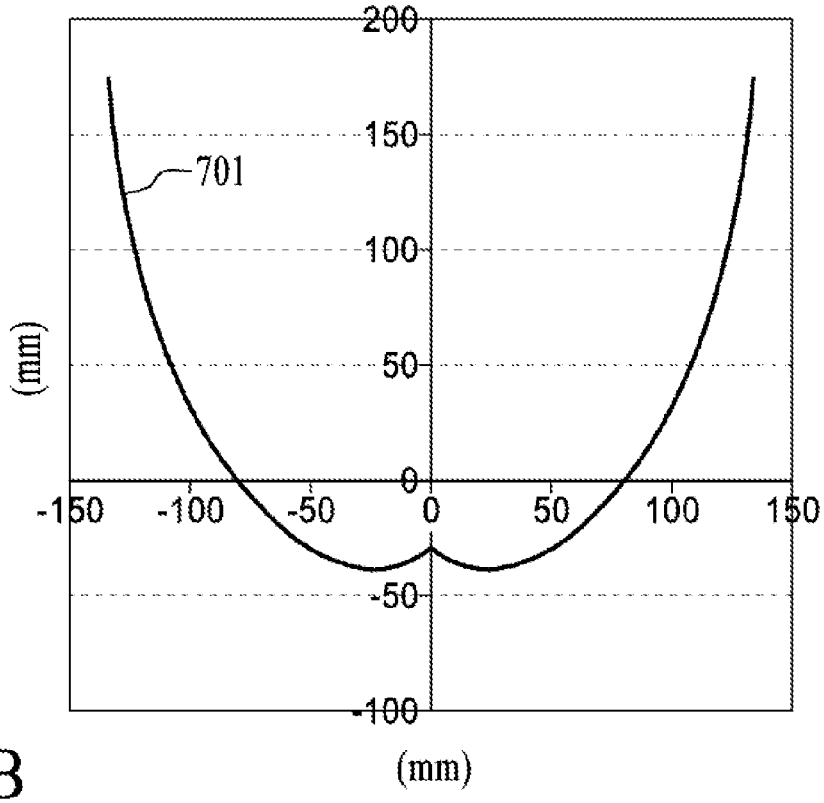

701
200
150
100
50
0
-50
-100
(mm)
-150
-100
-50
0
50
100
150
(mm)

FIG. 9B

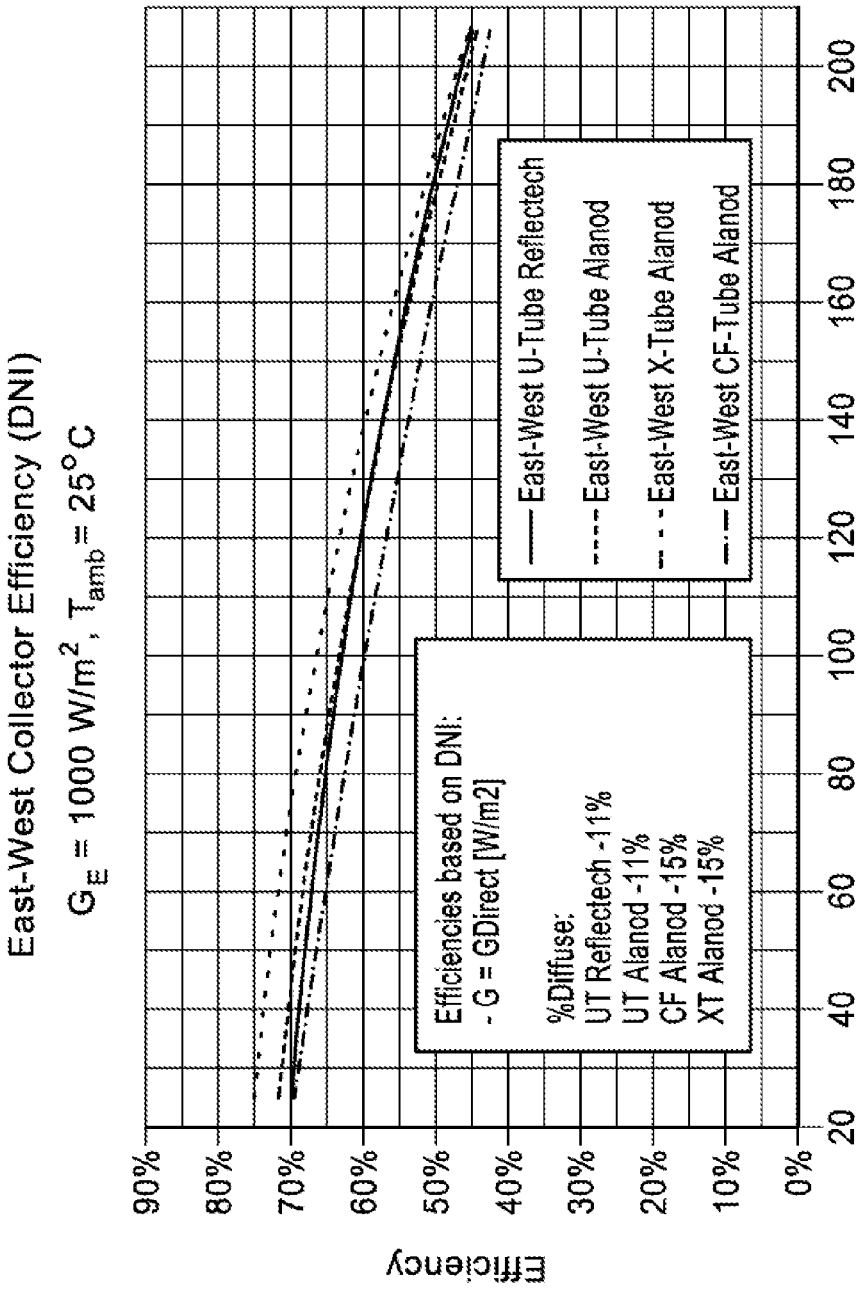

East-West Collector Efficiency (DNI)
G_E = 1000 W/m^2, T_{amb} = 25°C
Efficiencies based on DNI:
- G = GDirect [W/m2]
%Diffuse;
UT Reflectech -11%
UT Alanod -11%
CF Alanod -15%
XT Alanod -15%
East-West U-Tube Reflectech
East-West U-Tube Alanod
East-West X-Tube Alanod
East-West CF-Tube Alanod
Efficiency
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
20
40
60
80
100
120
140
160
180
200
T_{in} ' [°C]

FIG. 10A

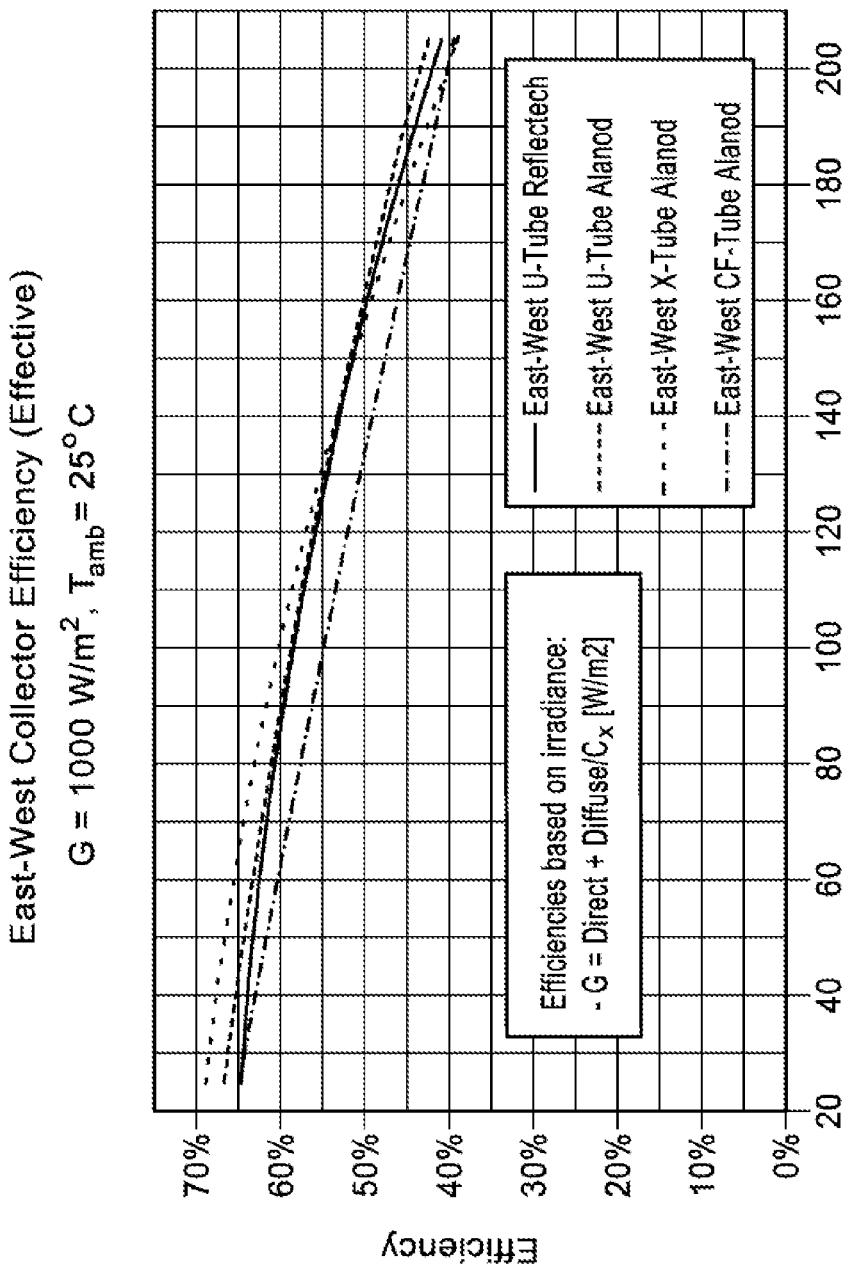

East-West Collector Efficiency (Effective)
G = 1000 W/m², T_amb = 25°C
Efficiency
70%
60%
50%
40%
30%
20%
10%
0%
20
40
60
80
100
120
140
160
180
200
T_in' [°C]
Efficiencies based on irradiance:
- G = Direct + Diffuse/C_X [W/m2]
East-West U-Tube Reflectech
East-West U-Tube Alanod
East-West X-Tube Alanod
East-West CF-Tube Alanod

FIG. 10B

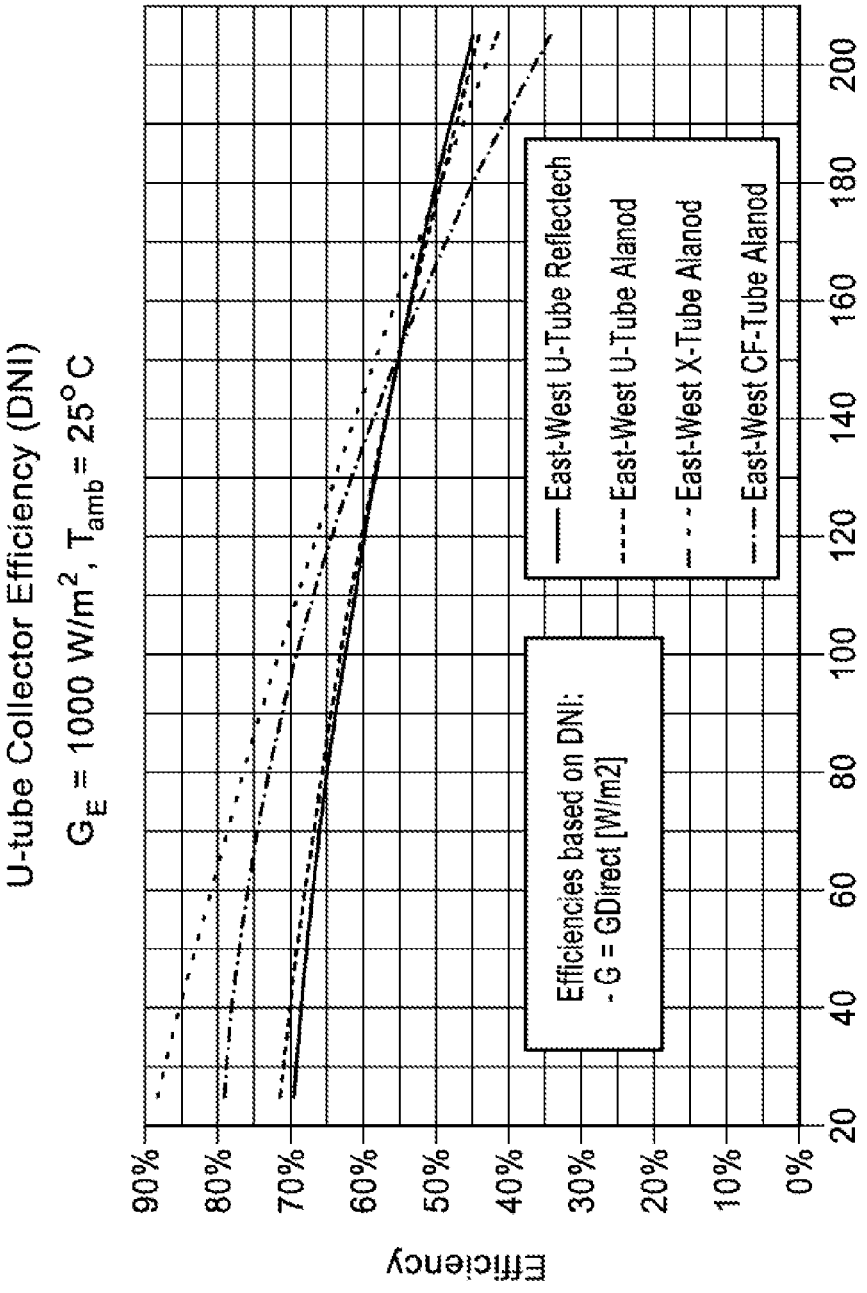

U-tube Collector Efficiency (DNI)
G_E = 1000 W/m^2, T_{amb} = 25°C
Efficiency
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
20
40
60
80
100
120
140
160
180
200
T_{in} ' [°C]
Efficiencies based on DNI:
- G = GDirect [W/m2]
East-West U-Tube Reflectech
East-West U-Tube Alanod
East-West X-Tube Alanod
East-West CF-Tube Alanod

FIG. 11A

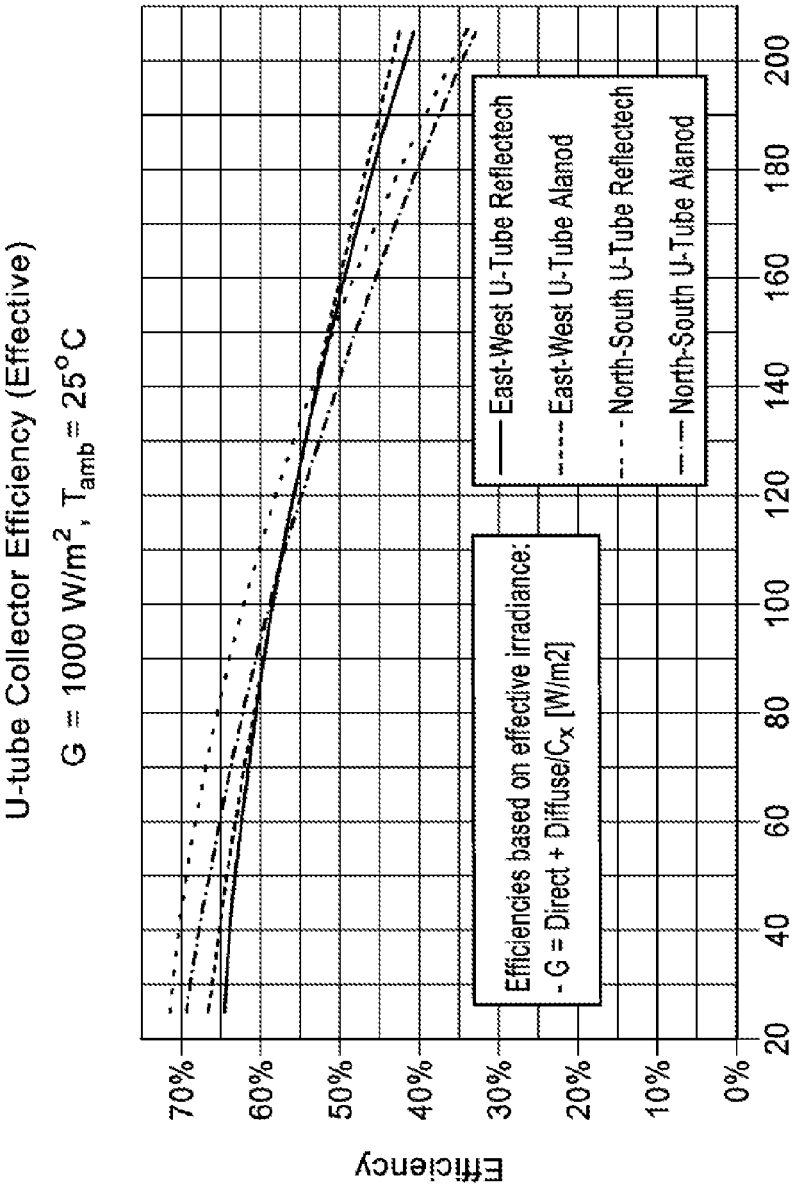

U-tube Collector Efficiency (Effective)
G = 1000 W/m², T_amb = 25°C
Efficiency
70%
60%
50%
40%
30%
20%
10%
0%
20
40
60
80
100
120
140
160
180
200
T_in ' [°C]
East-West U-Tube Reflectech
East-West U-Tube Alanod
North-South U-Tube Reflectech
North-South U-Tube Alanod
Efficiencies based on effective irradiance:
- G = Direct + Diffuse/C_x [W/m2]

FIG. 11B

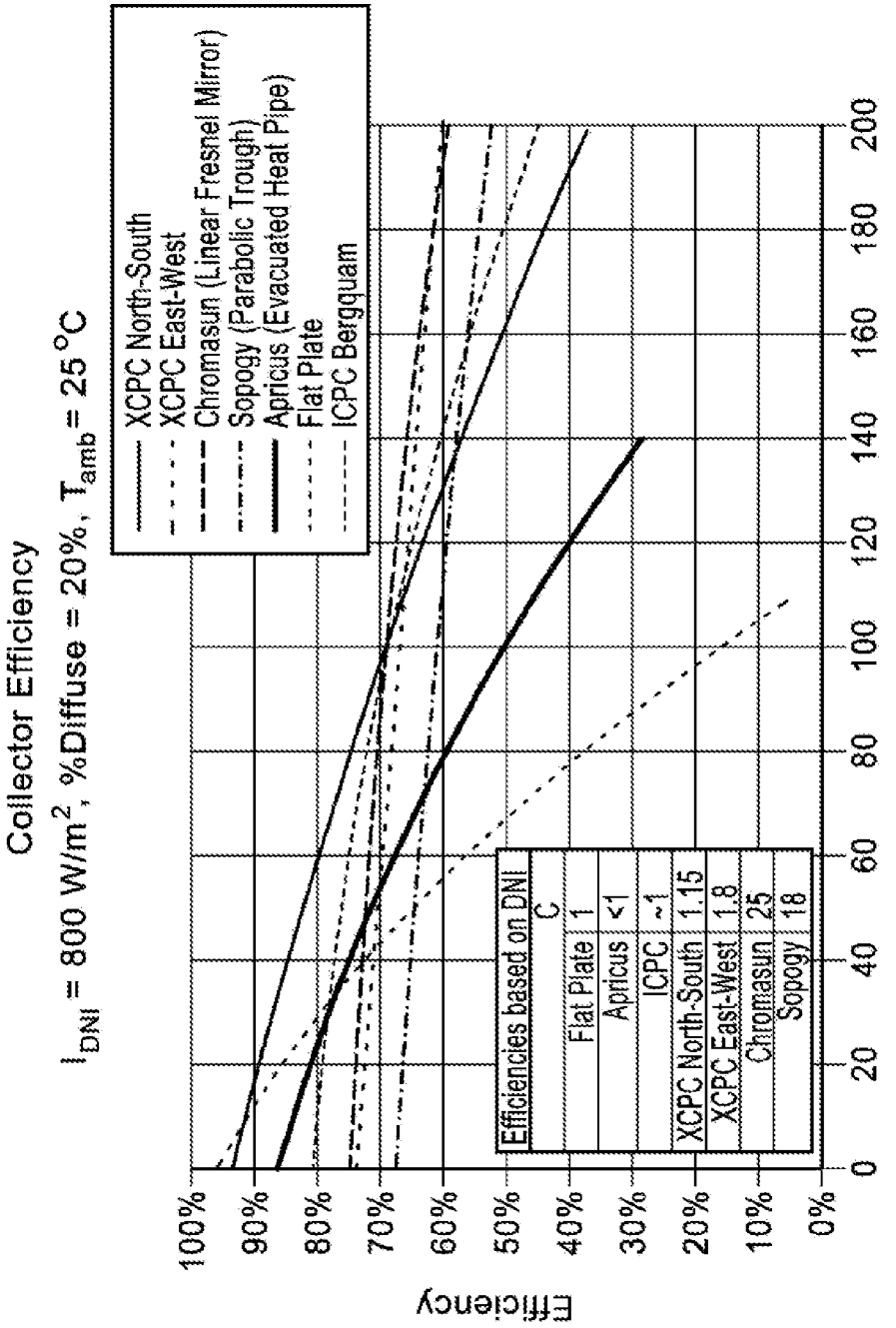

Collector Efficiency
I_{DNI} = 800 W/m^2, %Diffuse = 20%, T_{amb} = 25 °C
XCPC North-South
XCPC East-West
Chromasun (Linear Fresnel Mirror)
Sopogy (Parabolic Trough)
Apricus (Evacuated Heat Pipe)
Flat Plate
ICPC Bergquam
Efficiencies based on DNI
C
Flat Plate 1
Apricus <1
ICPC ~1
XCPC North-South 1.15
XCPC East-West 1.8
Chromasun 25
Sopogy 18
Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
20
40
60
80
100
120
140
160
180
200
Mean Temperature Above Ambient (T_m-T_{amb}) [°C]

FIG. 11C

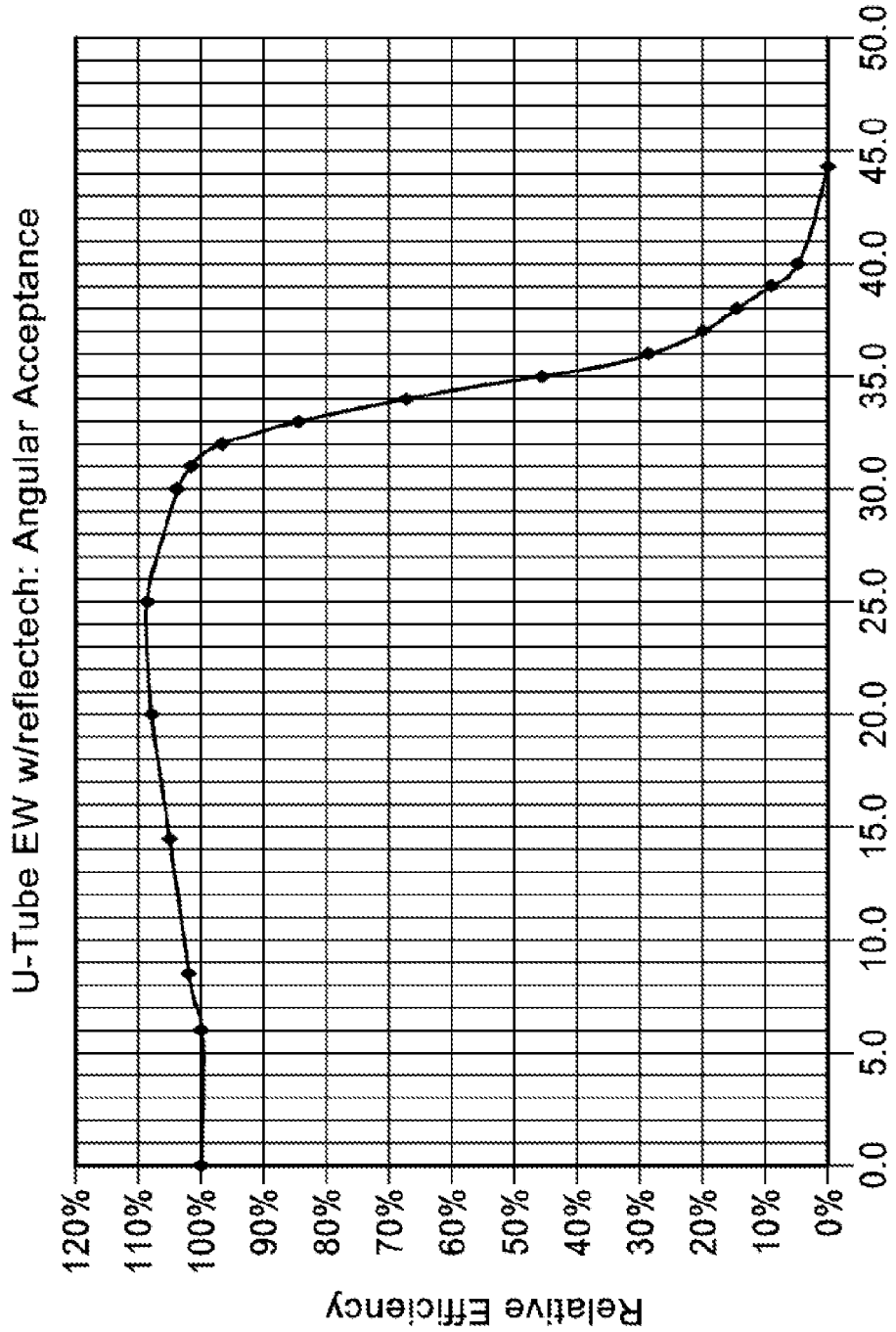

U-Tube EW w/reflectech: Angular Acceptance
Relative Efficiency
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Angle [Degrees]

FIG. 12

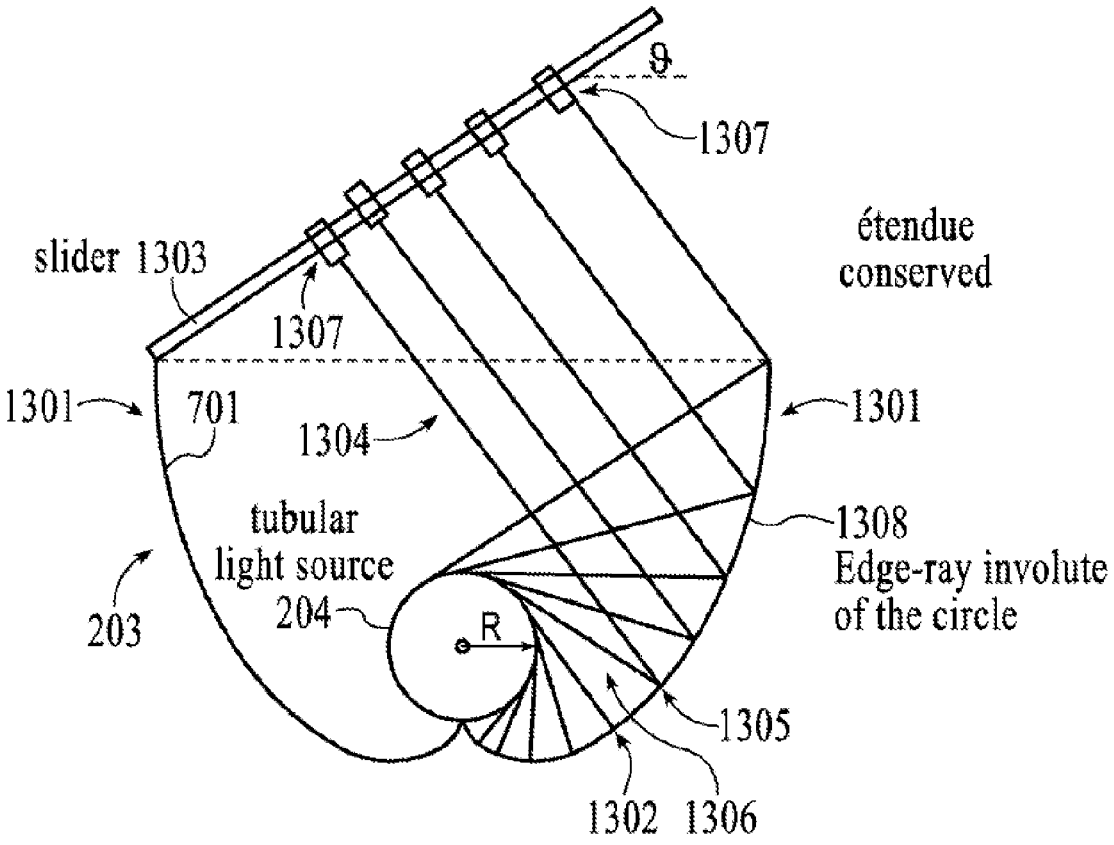

9
1307
étendue
conserved
slider 1303
1307
1301
701
1304
1301
tubular
light source
1308
Edge-ray involute
of the circle
203
204
R
1305
1302
1306

FIG. 13

FIG. 14A

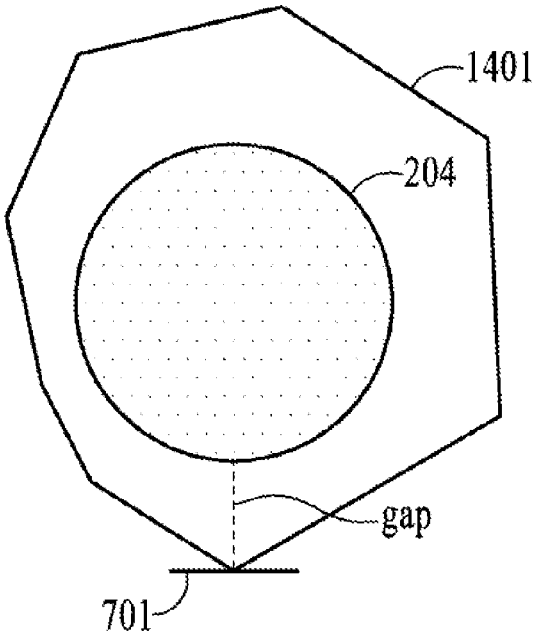
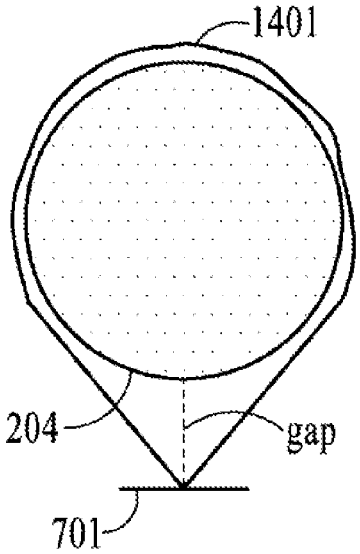


FIG. 14B



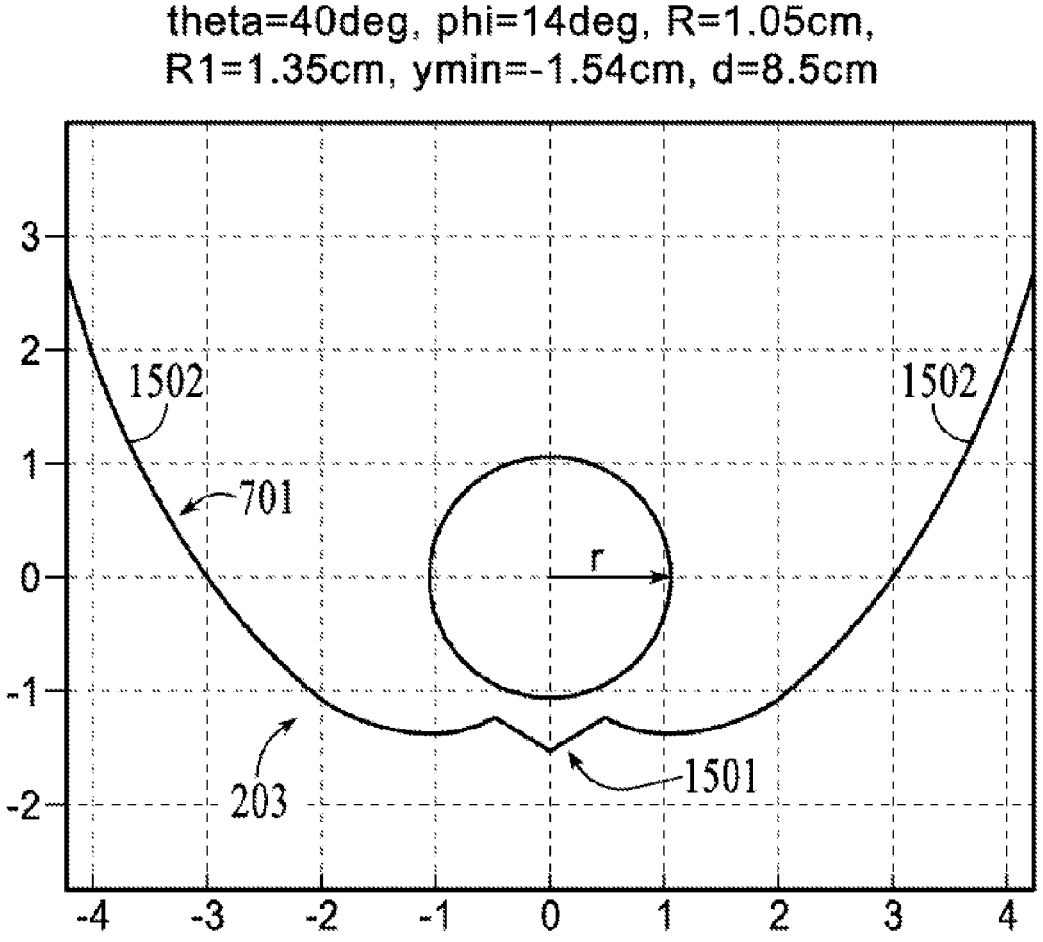

theta=40deg, phi=14deg, R=1.05cm,
R1=1.35cm, ymin=-1.54cm, d=8.5cm
1502
1502
701
r
203
1501
3
2
1
0
-1
-2
-4
-3
-2
-1
0
1
2
3
4

FIG. 15A

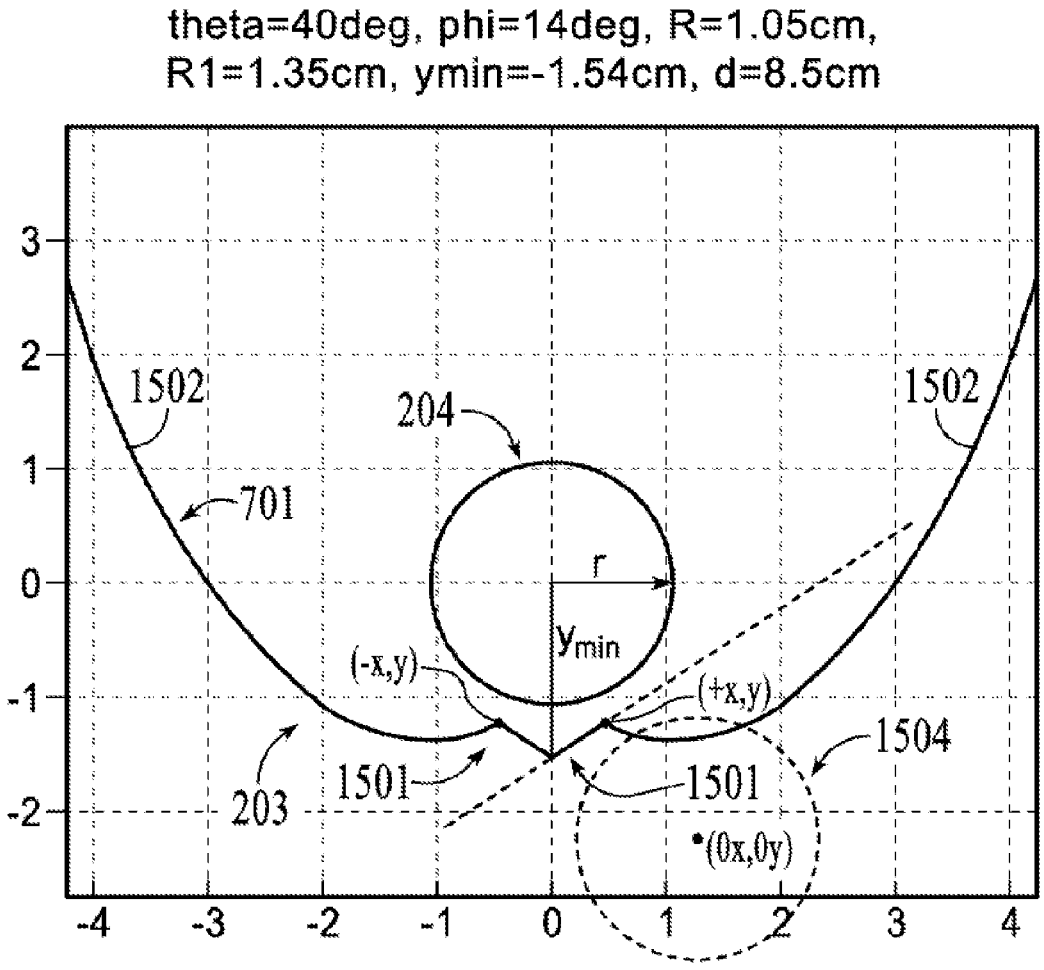

theta=40deg, phi=14deg, R=1.05cm,
R1=1.35cm, ymin=-1.54cm, d=8.5cm
1502
204
1502
701
r
ymin
(-x,y)
(+x,y)
1504
1501
1501
203
(0x,0y)
3
2
1
0
-1
-2
-4
-3
-2
-1
0
1
2
3
4

FIG. 15B

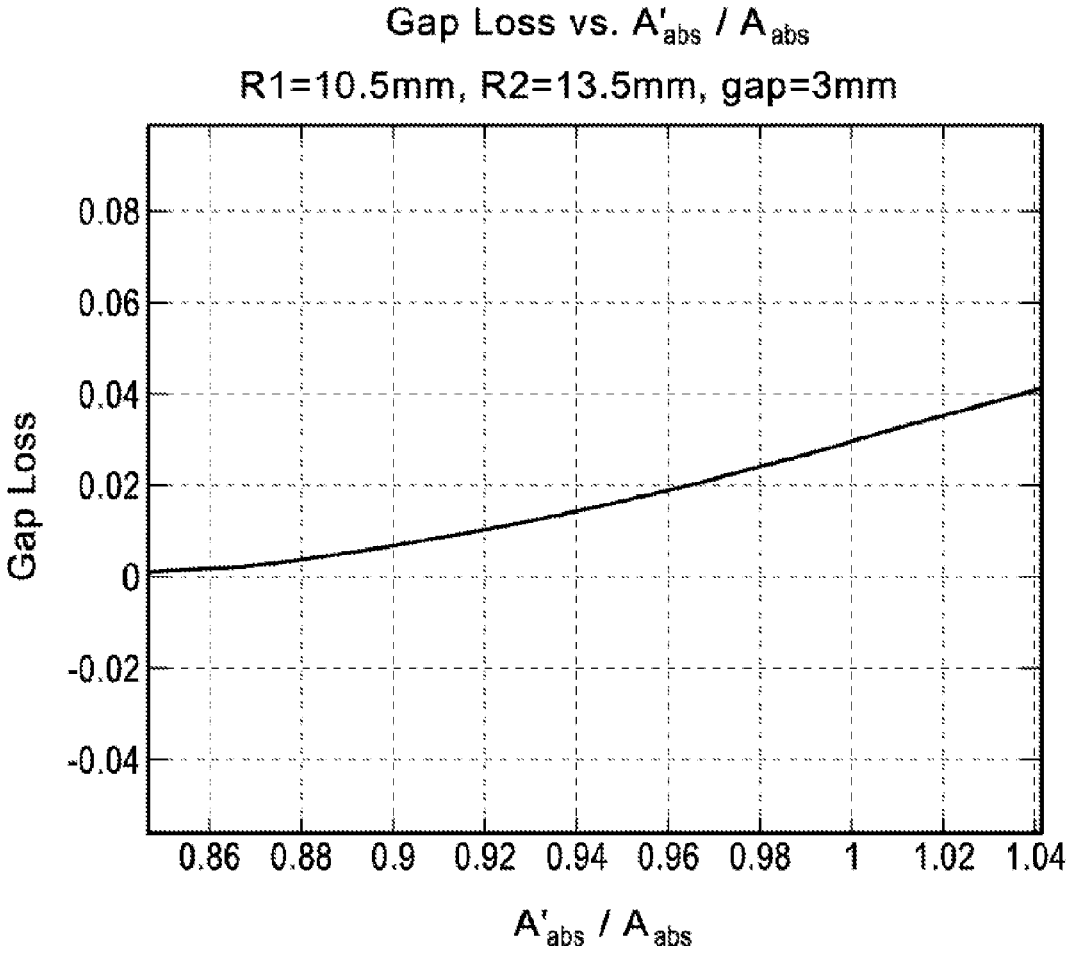
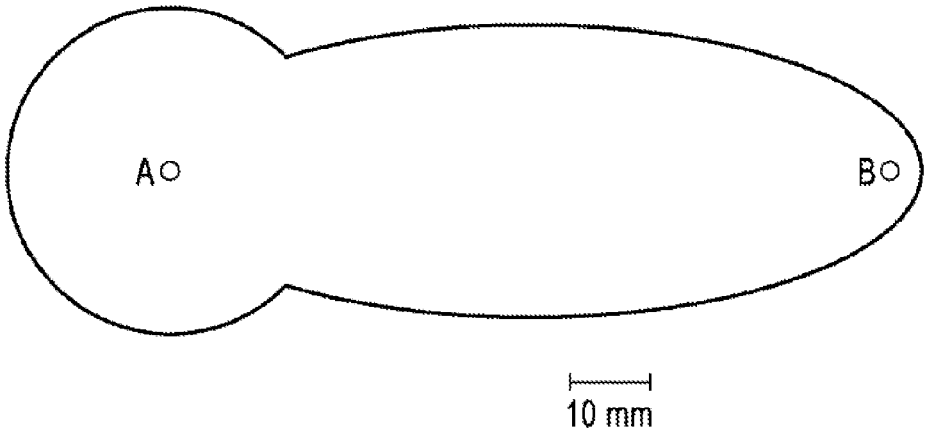

Gap Loss vs. A'abs / Aabs
R1=10.5mm, R2=13.5mm, gap=3mm
Gap Loss
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
1.02
1.04
A'abs / Aabs

FIG. 16



The ellipsoid paradox: the ellipsoid images B at A "perfectly" and the sphere images A on itself "perfectly".

FIG. 17A

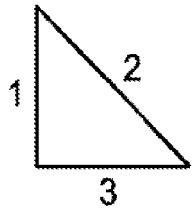


FIG. 17B

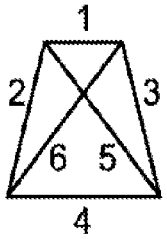


FIG. 17C

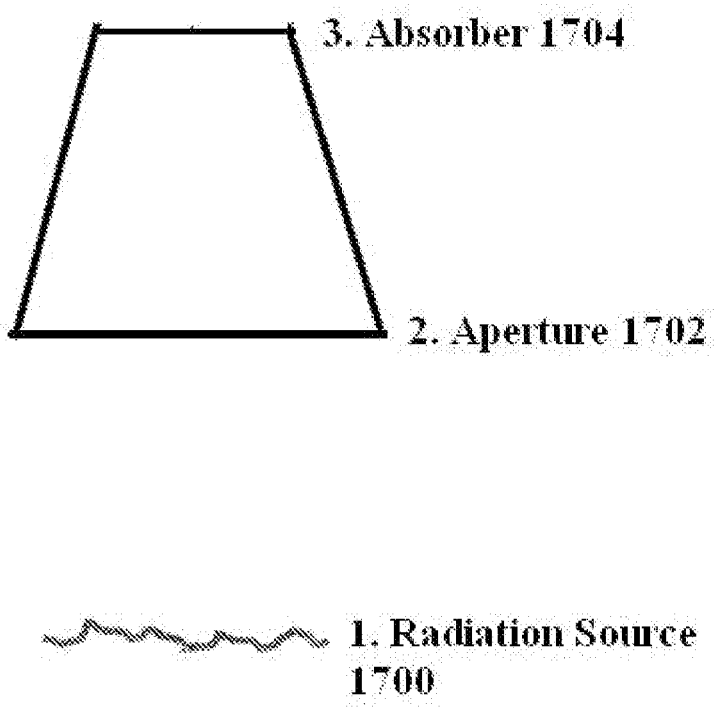
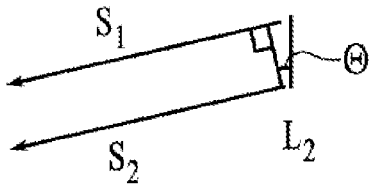


FIG. 17D

FIG. 18



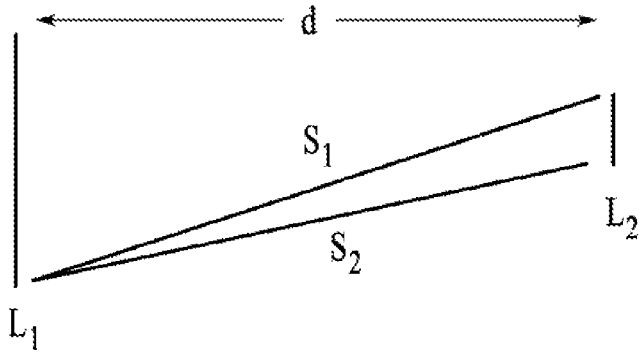


FIG. 19

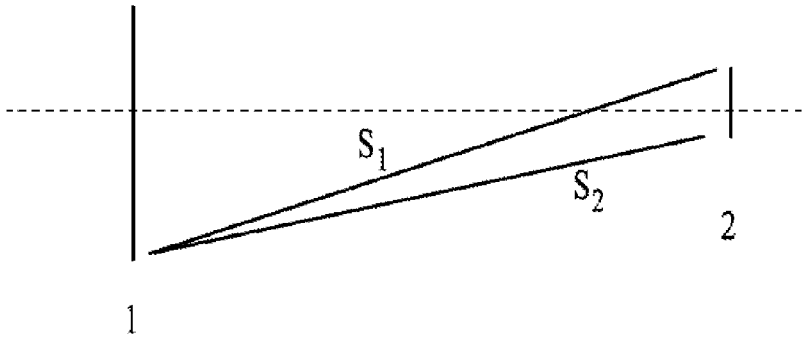


FIG. 20

SOLAR THERMAL CONCENTRATOR APPARATUS, SYSTEM, AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] 1. This application is a continuation patent application of U.S. patent application Ser. No. 14/663,455, titled "Solar Thermal Concentrator Apparatus, System, And Method", filed on Mar. 20, 2015 in the United States Patent and Trademark Office which is a continuation patent application of non-provisional patent application Ser. No. 13/153,802, titled "Solar Thermal Concentrator Apparatus, System, And Method", filed Jun. 6, 2011 in the United States Patent and Trademark Office, which claims the benefit of U.S. provisional patent application No. 61/385,890, filed on Sep. 23, 2010 in the United States Patent and Trademark Office.

[0002] 2. The specifications of the above referenced applications are incorporated herein by reference in their entirety.

STATEMENT OF RIGHTS UNDER THE INVENTION

[0003] This invention was made with government support. The invention was made with the State of California's support under the California Energy Commission contract No. 5005-05-21. The Energy Commission has certain rights to this invention.

BACKGROUND OF THE INVENTION

[0004] This disclosure relates to devices for the transmission of radiation, especially of light. In particular, it is related to a non-focusing reflector for the concentration of radiation such as sunlight at a desired region over a wide range of angles of incidence.

[0005] A number of systems for passive or non-tracking reflecting concentration of solar energy have been produced in the past. Among such systems are those shown in U.S. Pat. Nos. 5,537,991; 4,002,499; 4,003,638; 4,230,095; 4,387,961; 4,359,265; 5,289,356; and 6,467,916, which are all incorporated by reference in their entirety. It is appropriate to refer to the reflectors as light-transmission devices because it is immaterial whether the reflectors are concentrating radiation from a large solid angle of incidence (e.g. concentrating solar light onto a solar cell) or broadcasting radiation from a relatively small source to a relatively large solid angle (e.g. collecting light from an LED chip to form a beam).

[0006] Concentration of radiation is possible only if the projected solid angle of the radiation is increased. This requirement is the direct consequence of the law of conservation of the etendue, which is the phase space of radiation. Solar concentrators which achieve high concentration must track the sun; that is, they must continuously reorient in order to compensate for the apparent movement of the sun in an earth center (Ptolemaic) coordinate system. Reflectors, in contrast, are fixed in position for most lighting purposes. For tracking collectors the direction to the center of the sun is stationary with respect to their aperture. Such concentrators can achieve very high concentrations of about 45,000 in air. Even higher concentrations have been achieved inside transparent media.

[0007] Tracking, however, is technically demanding because solar collectors are commonly fairly large and designing these systems for orientational mobility may add significantly to their cost. Moreover, the absorber, which typically incorporates some heat transfer fluid as well as piping, also may need to be mobile. This is the motivation to study the concentration which can be achieved with stationary, non-tracking devices. The same principles apply when it is desired to deliver light or other radiant energy from a small source to a relatively large solid angle.

SUMMARY OF THE INVENTION

[0008] The inventor has realized that a concentrator assembly may be used, e.g., to collect solar energy to produce heat. Embodiments of the concentrator assembly feature a wide acceptance angle, allowing for use in non-tracking applications. Embodiments of the concentrator assembly feature a high collection efficiency (e.g., about 50% or greater) at high operating temperatures (e.g., 150 C or more, 200 C or more, etc.).

[0009] In one aspect, an apparatus is disclosed for concentrating light to an elongated absorber including: a trough shaped reflector extending along a longitudinal axis having at least one reflective surface having a shape which substantially corresponds to an edge ray involute of the absorber.

[0010] In some embodiments, the reflector has a first side and a second side disposed symmetrically on opposing sides of an optic plane transverse the longitudinal axis. Each side of the reflector includes a reflective surface having a shape which substantially corresponds to an edge ray involute of the absorber.

[0011] In some embodiments, the absorber includes a cylindrical absorber extending in the direction of the longitudinal axis and disposed at the bottom of the trough shaped reflector.

[0012] In some embodiments, the reflector includes an entrance aperture located at a top of the trough. In some embodiments, substantially all light incident on the entrance aperture at angles less than an acceptance angle are concentrated to the absorber.

[0013] In some embodiments, the reflector concentrates light at the thermodynamic limit.

[0014] In some embodiments, the absorber is spaced apart from the reflector by a gap distance; and a portion of the reflector at the bottom of the trough includes a reflective cavity having a reflective surface with a shape that deviates substantially from the edge ray involute of the absorber.

[0015] In some embodiments, the cavity includes a V-shaped trough extending along the bottom of the reflector in the direction of the longitudinal axis.

[0016] In some embodiments, the V-shaped trough includes an aperture positioned such that the image of the absorber reflected in a wall of the V-shaped trough has a top which is positioned proximal or above the aperture of the V-shaped top in the direction extending from the top of the trough to the bottom of the trough.

[0017] Some embodiments are characterized by an efficiency loss averaged over the acceptance angle relative to an equivalent gapless concentrator of 0.02 or less.

[0018] Some embodiments are characterized by a concentration ratio equal to at least 90% of that of an equivalent gapless concentrator.

[0019] In some embodiments, the gap distance is less than a radius of the absorber.

[0020] In some embodiments, the reflector concentrates light to the absorber with a concentration ratio C of 1.0 or greater, of 1.25 or greater, of 1.5 or greater, of 1.75 or greater, of 2.0 or greater, or more.

[0021] In some embodiments, a reflective surface of the reflector has a reflectivity of 90% or more for solar light.

[0022] In some embodiments, a reflective surface of the reflector has a reflectivity of 94% or more for solar light.

[0023] In some embodiments, the reflector has an acceptance angle of at least 25 degrees, at least 35 degrees, or at least 45 degrees, or at least 60 degrees, or more.

[0024] In another aspect, an apparatus for concentrating light to an absorber is disclosed including: at least one reflective surface configured to receive light incident at angles less than an acceptance angle and concentrate the received light to the absorber. The concentrator is characterized in that substantially any light ray emitted from the absorber would exit the concentrator without returning to the absorber. In some embodiments, at least one reflective surface includes a surface which corresponds to an edge ray involute of the absorber.

[0025] In another aspect, an apparatus is disclosed for converting incident solar light to heat, including: an evacuated tubular enclosure extending along a longitudinal axis from a proximal end to a distal end; a tubular absorber element located within the evacuated enclosure, and including a selective surface configured to absorb solar light incident through the evacuated enclosure and convert the solar light to heat; and a U-shaped tube in thermal contact with the absorber element. The U-shaped tube may include: a fluid input and a fluid output located at the proximal end of the tubular enclosure; an input portion extending from the fluid input along an interior surface of the tubular absorber element; and an output portion extending from the fluid output along an interior surface of the tubular absorber element; and a curved portion located proximal the distal end of the enclosure and providing fluid communication between the input and output portions. In some embodiments, the input portion and the output portion are spaced apart.

[0026] In some embodiments, fluid input into the fluid input at a first temperature travels though the U-shaped tube, absorbs heat from the selective absorber, and is output from the output at a second temperature higher than the first.

[0027] In some embodiments, the selective surface has an absorptivity of at least 0.75 and an emissivity of 0.25 or less at temperatures greater than 100 C.

[0028] In some embodiments, the selective surface has an absorptivity of at least 0.9 and an emissivity of 0.1 or less at temperatures greater than 100 C.

[0029] In some embodiments, the selective surface has an absorptivity of at least 0.9 and an emissivity of 0.1 or less at temperatures greater than about 200 C.

[0030] In another aspect, an apparatus is disclosed for concentrating light to an elongated absorber including: a trough shaped reflector extending along a longitudinal axis, the reflector spaced apart from the absorber. In some embodiments, the reflector has a portion of at least one reflective surface having a shape which substantially corresponds to an edge ray involute of a virtual absorber surrounding the absorber and contacting the reflector.

[0031] In some embodiments, the ratio of the area of the virtual absorber to the area of the absorber is 0.9 or greater.

[0032] In some embodiments, a portion of the reflector at the bottom of the trough includes a reflective cavity having a reflective surface with a shape that deviates substantially from the edge ray involute of the virtual absorber.

[0033] In some embodiments, the cavity includes a V-shaped trough extending along the bottom of the reflector in the direction of the longitudinal axis.

[0034] In some embodiments, the V-shaped trough includes an aperture positioned such that the image of the absorber reflected in a wall of the V-shaped trough has a top which is positioned proximal or above the aperture of the V-shaped top in the direction extending from the top of the trough to the bottom of the trough.

[0035] Some embodiments are characterized by an efficiency loss averaged over acceptance angle relative to an equivalent gapless concentrator of 0.02 or less.

[0036] In another aspect, a collector system is disclosed for converting solar light to heat including: a working fluid; at least one absorber element; and at least one concentrator. In some embodiments, the at least one concentrator concentrates solar light onto the absorber element to generate heat; and the working fluid flows through the absorber element to extract heat from the absorber element.

[0037] In some embodiments the at least one concentrator includes an apparatus of the type described above. In some embodiments, the absorber element includes an apparatus of the type described above.

[0038] In some embodiments, the system converts solar light to heat with an efficiency of about 30% or greater at an operating temperature of about 200 C or greater.

[0039] In some embodiments, the system converts solar light to heat with an efficiency of about 40% or greater at an operating temperature of about 200 C or greater.

[0040] In some embodiments, the system converts solar light to heat with an efficiency of about 45% or greater at an operating temperature of about 200 C or greater.

[0041] In some embodiments, the system converts solar light to heat with an efficiency of about 50% or greater at an operating temperature of about 200 C or greater.

[0042] In some embodiments, the system converts solar light to heat with an efficiency of about 30% or greater at an operating temperature of about 180 C or greater.

[0043] In some embodiments, the system converts solar light to heat with an efficiency of about 40% or greater at an operating temperature of about 180 C or greater.

[0044] In some embodiments, the system converts solar light to heat with an efficiency of about 45% or greater at an operating temperature of about 180 C or greater.

[0045] In some embodiments, the system converts solar light to heat with an efficiency of about 50% or greater at an operating temperature of about 180 C or greater.

[0046] In some embodiments, the system is characterized by an angular acceptance of at least 35 degrees.

[0047] In some embodiments, the system is characterized by an angular acceptance of at least 45 degrees.

[0048] In some embodiments, the system is characterized by an angular acceptance of at least 60 degrees.

[0049] In another aspect, a method is disclosed of converting solar light to heat including: using an apparatus of the type described above, concentrating light onto an absorber to generate heat.

[0050] In another aspect, a method is disclosed of converting solar light to heat including: receiving solar light with an apparatus of the type described above to generate heat.

[0051] In another aspect, a method is disclosed of converting solar light to heat including: receiving solar light with a system of the type described above to generate heat.

[0052] Various embodiments may include any of the above described features, either alone, or in combination.

BRIEF DESCRIPTION OF THE DRAWINGS

[0053] The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

[0054] FIG. **1** is an illustration of the solar geometry.

[0055] FIG. **2** is an illustration of a system for converting solar light into another form of energy.

[0056] FIG. **3**A is a side view of a concentrator assembly.

[0057] FIG. **3**B is a perspective view of a concentrator assembly.

[0058] FIG. **4**A is a top view of a concentrator assembly.

[0059] FIG. **4**B is a side view of a concentrator assembly.

[0060] FIG. **4**C is a cross section of an absorber used in the concentrator assembly of FIGS. **4**A-**4**B.

[0061] FIG. **5**A is a top view of a concentrator assembly.

[0062] FIG. **5**B is a side view of a concentrator assembly.

[0063] FIG. **5**C is a cross section taken transverse the longitudinal axis of an absorber used in the concentrator assembly of FIGS. **5**A-**5**B.

[0064] FIG. **5**D is a cross section taken through the longitudinal axis of an absorber used in the concentrator assembly of FIGS. **5**A-**5**B.

[0065] FIG. **6**A is a top view of a concentrator assembly.

[0066] FIG. **6**B is a side view of a concentrator assembly.

[0067] FIG. **6**C is a cross section taken transverse the longitudinal axis of an absorber used in the concentrator assembly of FIGS. **6**A-**6**B.

[0068] FIG. **6**D is a cross section taken through the longitudinal axis of an absorber used in the concentrator assembly of FIGS. **6**A-**6**B.

[0069] FIG. **6**E is a perspective view of an absorber used in the concentrator assembly of FIGS. **6**A-**6**B.

[0070] FIG. **7**A is an illustration of a cross-section of a concentrator assembly of a first embodiment.

[0071] FIG. **7**B is an illustration of a cross-section of a concentrator assembly of a second embodiment.

[0072] FIGS. **8**A-**8**E are ray traces of the concentrator assembly of FIG. **7** for rays incident at a variety of angles ranging from −35 degrees to +35 degrees.

[0073] FIGS. **9**A-**9**B are illustrations of exemplary reflective surfaces for a concentrator assembly.

[0074] FIGS. **10**A-**10**B show plots of collector efficiency versus inlet temperature under a variety of conditions.

[0075] FIGS. **11**A-**11**B show plots of collector efficiency versus inlet temperature under a variety of conditions.

[0076] FIG. **11**C shows a plot of collector efficiency versus inlet temperature under a variety of conditions for several types of collectors.

[0077] FIG. **12** is a plot of relative efficiency versus angle of incidence of solar light for an exemplary concentrator assembly.

[0078] FIG. **13** is an illustration of a concentrator design method.

[0079] FIGS. **14**A and **14**B illustrate the use of virtual absorbers in a concentrator design method.

[0080] FIGS. **15**A and **15**B illustrate a concentrator assembly featuring an absorber/concentrator gap, and a design method therefore.

[0081] FIG. **16** is a plot of the ratio of virtual absorber area to absorber area vs. gap loss for a concentrator assembly featuring an absorber/concentrator gap.

[0082] FIGS. **17**A-**20** show several embodiments of an optimal design concentration schematic.

DETAILED DESCRIPTION OF THE INVENTION

[0083] From a thermodynamic viewpoint, the solar geometry may be described in direction cosines, which are the momenta of the light rays. Referring to FIG. **1**, the sun over the year occupies a band **101** inside a unit radius circle **102** which is ±sin 23.5 deg. This band is nearly Vi the area of the circle, from which follows, e.g. as described in detail U.S. Pat. No. 6,467,916 to Roland Winston (incorporated herein by reference in its entirety), that the maximum theoretical concentration for a trough shaped concentrating reflector using no seasonal adjustments is very close to 2.

[0084] In some embodiments, this limit may be increased. In cases where the target (absorber) is immersed in a refractive material having an index of refraction (n), this limit is multiplied by n squared because the momentum of a light ray is actually the index of refraction x direction cosine. For example, for n~1.5 (typical of glass or PMMA) and restricting the absorber irradiance to 60 deg., the maximum concentration becomes ~3. In some embodiments featuring a low concentration design which can be switched seasonally between 2 positions each year (summer and winter) the limits are multiplied by 2 (4-6 concentration). For example, embodiments described herein may feature a concentration of about 4 or more.

[0085] FIG. **2** shows a system **200** for converting solar light into another form of energy, e.g., heat. A concentrator assembly **201** receives light from the sun. One or more concentrators concentrate the incident solar light onto one or more absorbers, which convert the light to heat. This heat is transferred from the concentrator assembly **201**, e.g., using a circulating heat transfer fluid to a heat exchanger **202**. The heat exchanger **202** outputs the heat received from the concentrator assembly **201**. The output heat may be used for any suitable purpose including, e.g., providing building heating, generation of electricity, generation of mechanical power, etc.

[0086] FIGS. **3** A and **3**B illustrate exemplary embodiments of the concentrator assembly **201**. The concentrator assembly **201** includes one or more optical concentrators **203**. Three concentrators **203** are shown in FIG. **3**A, five are shown in FIG. **3**B, and any other number may be used in other embodiments. Each concentrator **203** concentrates incident solar light onto a corresponding absorber **204**. The absorber **204** absorbs concentrated solar light and transforms it to heat.

[0087] As shown, the concentrators **203** and absorbers **204** are arranged in a linear array. However, any suitable arrangement may be used. The concentrators **203** are trough shaped reflectors having an open top end and tapering to a trough bottom. The inner surface of the trough is reflective,

e.g., with a reflectivity to solar light of e.g., 80% or more, 90% or more, 95% or more, etc. In some embodiments, the reflective surface may include a reflective coating, e.g., of the types available from Alanod Solar GmbH of Ennepetal, Germany and ReflecTech, Inc. of Arvada, Colo.

[0088] The absorbers **204** are elongated tubular (e.g., cylindrical) elements positioned at or near the bottom of the trough shaped reflectors. As shown, each of the concentrators **203** is symmetric about an optical plane (indicated with a dashed line in FIG. **3**A). In one embodiment, the concentrator **203** may include a U shape. In another embodiment, the concentrator **203** may include any shape known in the art so as to concentrate an optical amount of energy to a predetermined location. In some embodiments, a heat transfer working fluid (e.g., water, oil, an organic fluid, or any other suitable fluid known in the art) flows through the absorbers **204** (e.g., in a series arrangement, in a parallel arrangement, etc.). Heat from the absorbers **204** is transferred to the fluid, which flows out of the concentrator assembly **201** to the heat exchanger **202**. The energy preferably is captured and used for a predetermined purpose.

[0089] As shown, the concentrators **203** and corresponding absorbers **204** are arranged in a linear array. In some embodiments, the concentrators may be arranged with a center to center spacing of 1.0 m or less, 0.5 m or less, 0.25 m or less, 0.1 m or less, e.g., in the range of 100-400 mm. In some embodiments, the absorbers **204** may have an outer diameter of 100 mm or less, 75 mm or less, 50 mm or less, e.g., in the range of 40-60 mm.

[0090] As described greater detail below, in some embodiments, concentrators **203** concentrate substantially all solar light incident at angles to the optic plane less than an acceptance angle to the absorber **204**. In some embodiments, the concentrator **203** concentrates light incident at angles less than the acceptance angle with an efficiency at the thermodynamic limit. In some embodiments, the concentrator **203** concentrates light incident at angles less than the acceptance angle with a geometric concentration ratio of C of 1.0 or more, 1.1 or more, 1.25 or more, 1.5 or more, 1.75 or more, 1.85 or more, 1.9 or more, 2 or more, etc. In some embodiments this concentration is provided over the year without tracking.

[0091] FIGS. **4**A-**4**C illustrate an exemplary embodiment of the collector assembly **201** featuring absorbers **204** having a counter flow arrangement. As shown, absorbers **204** are cylindrical members having an outer transparent evacuated enclosure **401** (e.g., a glass tube). Located within the enclosure is a tubular absorber fin **403** (e.g., an extruded aluminum or copper pipe) which absorbs solar light incident through the enclosure **401** and transforms the light to heat. The absorber fin **401** may include a selective surface **405** which exhibits a high absorptivity to solar light and a low emissivity (thereby limiting radiative heat loss). For example, in some embodiments, the selective surface **405** may exhibit an absorptivity of 0.75 or more, 0.9 or more, 0.95 or more, 0.99 or more etc. (e.g., in the range of 0.9 to 0.99). For example, in some embodiments, the selective surface **405** may exhibit an emissivity of 0.25 or less, 0.10 or less, 0.05 or less, 0.025 or less etc. (e.g., in the range of 0.04 to 0.05). In some embodiments, the selective surface exhibits these absorptivity and emissivity properties at temperature of 100 C or greater, 150 C or greater, 175 C or greater, or 200 C or greater (e.g., in the range of 150-200 C). In some embodiments, the selective surface comprises an aluminum nitride coating, e.g., sputtered on to the outer (vacuum facing) surface of absorber fin **401**. In other embodiments, any other suitable surface or coating known in the art may be used.

[0092] Absorber fin **403** is disposed about an inner tube **407** (e.g., an extruded aluminum or copper pipe). Heat transfer working fluid flows in to the inner tube **407** to the end of the tube. The fluid returns from the end of the tube through an annular space between the inner tube **407** and the absorber fin **403** (i.e., in a "counter-flow" arrangement). As the fluid passes through the absorber **204**, the fluid absorbs heat from the absorber fin **403** and carries the heat away from the absorber **204**. That is, the fluid enters the absorber at a first temperature, is heated during its passage, and is output at a second temperature higher than the first temperature.

[0093] In some embodiments, absorber fin **403** may be made of glass (or other non-metallic material) and coated with a selective surface **405**. In some such embodiments, the absorber fin **403** and the enclosure **401** may be joined using only glass on glass seals, or may be constructed as an integral unit. Similarly, inner tube **407** may be made of glass (or other non-metallic material) allowing for the reduction or elimination of glass on metal seals and/or allowing absorber **204** to be formed as an integral or substantially integral unit. In one embodiment, the reflective material may comprise a reflective paint, or a mirrored surface.

[0094] Concentrator assembly **201** includes a plumbing system **409** which facilitates the flow of heat transfer fluid through the absorbers **204**. A pump **411** pumps fluid along an input plumbing line **412** and into the absorbers **204**. For example, pump **411** may pump the fluid with a mass flow rate of 40 g/s or more, 50 g/s or more, 60 g/s or more, 70 g/s or more, 80 g/s or more, e.g., in the range of 40-45 g/s. As described above, the fluid is heated during counter flow action. An output plumbing line **413** carries the heated fluid away from concentrator assembly **201**, e.g., to heat exchanger **202**. The pump **411** may be powered by various means and in one embodiment from the collected heat.

[0095] FIGS. **5**A-**5**D illustrate an exemplary embodiment of the collector assembly **201** featuring absorbers **204** having an alternative counter flow arrangement. As shown, absorbers **204** are cylindrical members having an outer transparent evacuated enclosure **401** (e.g., a glass tube). Located within the enclosure is a tubular absorber fin **403** (e.g., an extruded aluminum or copper pipe) which absorbs solar light incident through the enclosure **401** and transforms the light to heat. The absorber fin **403** may include a selective surface **405** which exhibits a high absorptivity to solar light and a low emissivity (thereby limiting radiative heat loss). For example, in some embodiments, the selective surface **405** may exhibit an absorptivity of 0.75 or more, 0.9 or more, 0.95 or more, 0.99 or more etc. (e.g., in the range of 0.9 to 0.99). For example, in some embodiments, the selective surface **405** may exhibit an emissivity of 0.25 or less, 0.10 or less, 0.05 or less, 0.025 or less etc. (e.g., in the range of 0.04 to 0.05). In some embodiments, the selective surface exhibits these absorptivity and emissivity properties at temperature of 100 C or greater, 150 C or greater, 175 C or greater, or 200 C or greater (e.g., in the range of 150-200 C). In some embodiments, the selective surface comprises an aluminum nitride coating, e.g., sputtered on to the outer

(vacuum facing) surface of absorber fin **401**. In other embodiments, any other suitable surface or coating known in the art may be used.

[0096] In contrast to the example shown in FIGS. **4**A-**4**C, in the absorber of the current example absorber fin **403** is not disposed about an inner tube **407**. Instead, a counter flow heat exchange pipe **501** runs along and is in thermal contact with the inner surface of the absorber fin **403**. The heat exchange pipe **501** includes an outer tube **502** closed at one end and disposed about an inner tube **503**. Heat transfer working fluid flows into the inner tube **503** to the end of the pipe **501**. The heat transfer fluid returns through the annular space between the inner tube **503** and the outer tube **502**. As the fluid passes through the absorber **204**, the fluid absorbs heat from the absorber fin **403** and carries the heat away from the absorber **204**. That is, the fluid enters the absorber at a first temperature, is heated during its passage, and is output at a second temperature higher than the first temperature. If the direction of flow is reversed, the heat exchange is still useful. Because of the high vacuum, the lowest resistance path for the heat is through the fluid.

[0097] Heat exchange pipe **501** may be, e.g., welded or otherwise joined to absorber fin **403**. In some embodiments, one or more portions of heat pipe **501** and one or more potions of absorber fin **403** are formed as an integral unit. In another embodiment, the pipe **501** may be connected by a mechanical fastener.

[0098] Concentrator assembly **201** includes a plumbing system **409** which facilitates the flow of heat transfer fluid through the absorbers **204**. A pump **411** pumps fluid along an input plumbing line **412** and into the absorbers **204**. For example, pump **411** may pump the fluid with a mass flow rate of 40 g/s or more, 50 g/s or more, 60 g/s or more, 70 g/s or more, 80 g/s or more, e.g., in the range of 40-45 g/s. As described above, the fluid is heated during counter flow action in heat pipe **501**. An output plumbing line **413** carries the heated fluid away from concentrator assembly **201**, e.g., to heat exchanger **202**.

[0099] FIGS. **6**A-**6**E illustrate an exemplary embodiment of collector assembly **201** featuring absorbers **204** having a so called U-tube flow arrangement. As shown, absorbers **204** are cylindrical members having an outer transparent evacuated enclosure **401** (e.g., a glass tube). Located within the enclosure is a tubular absorber fin **403** (e.g., an extruded aluminum or copper pipe) which absorbs solar light incident through the enclosure **401** and transforms the light to heat. The absorber fin **401** may include a selective surface **405** which exhibits a high absorptivity to solar light and a low emissivity (thereby limiting radiative heat loss). For example, in some embodiments, the selective surface **405** may exhibit an absorptivity of 0.75 or more, 0.9 or more, 0.95 or more, 0.99 or more etc. (e.g., in the range of 0.9 to 0.99). For example, in some embodiments, the selective surface **405** may exhibit an emissivity of 0.25 or less, 0.10 or less, 0.05 or less, 0.025 or less etc. (e.g., in the range of 0.04 to 0.05). In some embodiments, the selective surface exhibits these absorptivity and emissivity properties at temperature of 100 C or greater, 150 C or greater, 175 C or greater, or 200 C or greater (e.g., in the range of 150-200 C). In some embodiments, the selective surface comprises an aluminum nitride coating, e.g., sputtered on to the outer (vacuum facing) surface of absorber fin **401**. In other embodiments, any other suitable surface or coating known in the art may be used.

[0100] In contrast to the example shown in FIGS. **4**A-**4**C and FIGS. **5**A-**4**C, in the absorber of the current example absorber fin **403** is not disposed about an inner tube **407** and does not include a counter-flow heat exchange pipe **501**. Instead, a U-shaped tube **601** runs along and is in thermal contact with the inner surface of the absorber fin **403**. Heat transfer working fluid flows into the U-shaped tube **601** through an input at a proximal end of the absorber **204**. The fluid flows down an input portion of the tube to a distal end of absorber **204**. The end of the U-shaped tube **601** includes a curve portion which directs the fluid back through an output portion of the tube to an output located at the proximal end of the absorber **204**.

[0101] As the fluid passes through the absorber **204**, the fluid absorbs heat from the absorber fin **403** and carries the heat away from the absorber **204**. That is, the fluid enters the absorber at a first temperature, is heated during its passage, and is output at a second temperature higher than the first temperature. Note that the input portion and output portion of the U-shaped tube **601** are spaced apart from each other. Preferably, the spacing is optimized. Advantageously, the arrangement reduces or eliminates heat flow from the warmer fluid exiting the tube to the cooler fluid entering the tube. Accordingly, the efficiency of the heat exchange between the absorber **204** and the heat exchange working fluid is increased, e.g., in comparison to flow configurations featuring a counter-flow type arrangement.

[0102] U-shaped tube **601** may be, e.g., welded or otherwise joined to absorber fin **403**. In some embodiments, one or more portions of U-shaped tube **601** and one or more portions absorber fin **403** are formed as an integral unit, e.g., an integral unit of extruded metal (e.g., aluminum or copper).

[0103] Concentrator assembly **201** includes a plumbing system **409** which facilitates the flow of heat transfer fluid through the absorbers **204**. A pump **411** pumps fluid along an input plumbing line **412** and into the absorbers **204**. For example, pump **411** may pump the fluid with a mass flow rate of 40 g/s or more, 50 g/s or more, 60 g/s or more, 70 g/s or more, 80 g/s or more, e.g., in the range of 40-45 g/s. As described above, the fluid is heated during passage through the U-shaped tube **601**. An output plumbing line **413** carries the heated fluid away from concentrator assembly **201**, e.g., to heat exchanger **202**.

[0104] Although the embodiments shown above feature a direct flow plumbing configuration, it is to be understood that other plumbing configurations known in the art may be used. For example, in some plumbing configurations, pump **411** is omitted, and the flow of the heat transfer working fluid is driven, e.g., by gravity or thermal convection.

[0105] FIG. **7**A illustrates a cross-section of a concentrator assembly **201** of a first embodiment. The concentrator assembly **201** illustrated in FIG. **7**A shows a cross section of a trough shaped reflective surface **701** of concentrator **203** designed for the absorber fin of FIG. **4**. FIG. **7**B illustrates a cross-section of a concentrator assembly **201** of a second embodiment. The concentrator assembly **201** illustrated in FIG. **7**B shows a cross section of a trough shaped reflective surface **701** of concentrator **203** designed for the absorber fin of FIGS. **5** and **6**. The reflective surface **701** illustrated in FIGS. **7**A and **7**B extends in and out of the plane of the page along a longitudinal axis. Cylindrical absorber **204** is located at the bottom of the trough and also extends along the direction of the longitudinal axis. The top of the trough

forms an input aperture. The reflective surface is shaped such that substantially all light rays incident on the input aperture at angles less than an acceptance angle are directed to a surface of absorber **204** (e.g., the surface of a cylindrical absorber fin **403** of absorber **204**). FIGS. **8**A-**8**E are ray traces of the reflector surface **701** of FIG. **7**A, which illustrate the concentration of light at angles less than an acceptance angle of 34 degrees. The ray traces of the reflector surface **701** of a different shape, for example the reflector surface illustrated in FIG. **7**B, would be very similar.

[0106] The acceptance angle can be designed according to the desired concentration factor, the concentrated flux profile and the orientation of the absorber tubes (East-West or North-South, horizontal or tilted, etc.). In one embodiment, the tilt may be determined based on a location of system. Orienting the absorber tubes North-South (N-S) requires larger acceptance angles to ensure sufficient illumination throughout the day, which reduces the concentration factor. Therefore, an East-West (E-W) orientation is generally advantageous. However, a N-S oriented reflector (with the larger acceptance angle) does accept more diffuse solar irradiation and so too has some positive performance attributes. Additionally, reflectors with larger acceptance angles will generally require less reflector area, which provides an economic advantage. FIGS. **9**A and **9**B show exemplary shapes for the reflective surface **701**. In FIG. **9**A the surface **701** has been optimized for use with a concentrator **204** oriented in the N-S direction and has an acceptance angle of 60 degrees. In FIG. **9**B the surface **701** has been optimized for use with a concentrator **204** oriented in the E-W direction, with an acceptance angle of 34 degrees.

[0107] FIGS. **10**A-**10**B illustrate plots of collector efficiency versus heat exchange fluid intake temperature for concentrator assemblies **201** in various configurations. The collector efficiency is defined as the ratio of the useful power extracted from the collector divided by the product of the collected irradiance and the effective aperture area of the collector (defined as the length of the active area of the absorber tube **204**, which is the area covered by the selective coating **405**, times the width of the reflector). Various collector efficiencies may change depending on one or more parameters and the plot forms no limitations to the present disclosure.

[0108] Plots are shown for concentrator assemblies with absorbers **204** in the U-Tube (e.g., as shown in FIGS. **6**A-**6**E), X-Tube (the X-tube has similar heat exchange properties to the counter flow tube), and counter flow (CF) (e.g., as shown in FIGS. **5**A-**5**D) configurations. In each case, the concentrator assemblies are in the E-W arrangement. The type of reflective surface used is indicated (i.e. 92% reflectivity material available from Alanod or 94% reflectivity material available from ReflecTech). In each case the ambient temperature is 25 C, and the incident solar irradiance is G=1000 W/m^2. FIG. **10**A shows efficiencies based on direct normal incidence (DNI). FIG. **10**B shows efficiencies based on effective irradiance (i.e., the direct irradiance plus the diffuse irradiance divided by the concentration ratio of the concentrator assembly).

[0109] Referring to FIGS. **10**A and **10**B, at an inlet temperature of 200 C, the U-Tube configuration (with ReflecTech and Alanod reflective surfaces) provides the highest collector efficiency of about 45% or more. At an inlet temperature of 200 C, the X-Tube and CF configurations provide similar collector efficiency in comparison to each other, but inferior efficiency compared to the U-Tube configuration. However, for inlet temperatures in the range of 40 C to 140 C, the X-Tube configuration provides the best performance of any configuration.

[0110] FIGS. **11**A and **11**B are plots of collector efficiency versus heat exchange fluid intake temperature for concentrator assemblies **201** in various configurations. The collector efficiency is defined as the ratio of the useful power extracted from the collector divided by the product of the collected irradiance and the effective aperture area of the collector (defined as the length of the active area of the absorber tube **204**, which is the area covered by the selective coating **405**, times the width of the reflector).

[0111] Plots are shown for concentrator assemblies with absorbers **204** in the U-Tube (e.g., as shown in FIGS. **6**A-**6**E) configuration for both E-W and N-S arrangement. The type of reflective surface used is indicated (i.e. 92% reflectivity material available from Alanod or 94% reflectivity material available from ReflecTech). In each case the ambient temperature is 25 C, and the incident solar irradiance is G=1000 W/m^2. FIG. **11**A shows efficiencies based on direct normal incidence (DNI). FIG. **11**B shows efficiencies based on effective irradiance (i.e., the direct irradiance plus the diffuse irradiance divided by the concentration ratio of the concentrator assembly).

[0112] Referring to FIGS. **11**A and **11**B, at an inlet temperature of 200 C, the U-Tube configuration (with ReflecTech and Alanod reflective surfaces) with E-W arrangement provides the highest collector efficiency of about 45% or more. At 200 C, the N-S arrangement provides inferior efficiency compared to E-W. However, for inlet temperatures in the range of 40 C to 140 C, the N-S arrangement provides better performance than the E-W arrangement.

[0113] FIG. **11**C shows plots of collector efficiency versus operating temperature (mean temperature above ambient) for concentrator assemblies **201** in comparison to collector efficiencies of other types of collectors known in the art. The collector efficiency is defined as the ratio of the useful power extracted from the collector divided by the product of the collected DNI irradiance and the effective aperture area of the collector. In each case the ambient temperature is 25 C, and the incident solar irradiance is G=800 W/m^2. The concentration ratio for each collector type is indicated.

[0114] Plots are shown for concentrator assemblies with absorbers **204** in the U-Tube (e.g., as shown in FIGS. **6**A-**6**E) configuration for both E-W and N-S arrangement. Plots are also shown for three non-tracking collectors: a flat plate solar collector, an Apricus evacuated heat pipe collector, and a Winston/Bergquam collector featuring an evacuated tube having an internally located non-imaging (compound parabolic concentrator) collector. Plots are also shown for two tracking collectors: a Chromasun linear Fresnel mirror collector and a Sopogy parabolic trough collector.

[0115] Referring to FIG. **11**C, note that at temperatures near 200 C, the U-Tube E-W concentrator outperforms all other collectors (tracking or non-tracking). Further at temperatures in the range of 100-200 C, the U-Tube E-W and U-Tube N-S concentrators perform much better than the non-tracking flat plate and Apricus collectors, and comparable to or better than the remaining collectors.

[0116] FIG. **12** shows a plot of the relative efficiency of a collector featuring an E-W oriented absorber in the U-tube

configuration as a function of the angle of incident solar radiation. Note that the relative efficiency is substantially constant at about 100% over angles less than the 35 degree acceptance angle of the concentrator **203** designed for E-W.

[0117] In the examples described above, it is advantageous if the reflective surface **701** of the concentrators **203** has a shape which ensures that all or substantially all (e.g., in the absence of losses such as those due to imperfect reflectivity) light rays incident on the concentrator **203** at angles less than an acceptance angle are concentrated to an absorber. This condition provides for efficient use of the absorber **204**, which, in many applications is a costly component, e.g., with a cost that increases with size.

[0118] In some embodiments, the shape of the reflective surface **701** may be determined by considering the active surface of absorber **204** (e.g., selective surface **405**) to be a light emitting surface and requiring that the reflective surface **701** be shaped such that no light rays emanating from the surface of absorber **204** return to the absorber **204**. In the terminology of radiation transfer, the view factor from absorber back to itself is zero. It follows from energy conservation that light starting from the emitting surface will (after zero, one or more reflections) invariably reach the sky. The shape factor is one. Note, that in this discussion, it is understood that material losses, like imperfect reflectivity are not included. In one embodiment, the radiation shape factor from the desired phase space of the sky is also at maximum, the shape factor from desired phase space of sky to light emitting surface is also one. In special cases, both shape factors can be one, giving a class of non-imaging optical concentrators described. However, in most cases this is not practical and a compromise solution is sought. The following describes methods for ensuring the shape factor from the absorber is one, which is frequently the option. The following also describes techniques for obtaining improved or optimal designs which take into account practical considerations for real absorbers, e.g., concentrator/absorber gaps. For example, the shape may comprise involutes of a circle arc. For example, the shape may also comprise parabolic shape for the concentrator.

[0119] For example, FIG. **13** illustrates a method of designing a concentrator **203** for a cylindrical absorber **204** in which the shape factor from the absorber is one. Here, the active surface of the absorber is taken to be the outer surface of the cylinder. The reflective surface **701** of the concentrator **203** includes two symmetrically disposed edge ray involutes **1301** of the cylinder.

[0120] As used herein, an edge ray involute of an absorber is a curve determined using the following procedure. A taught string is considered to be wrapped around the absorber **204**. While maintaining the string taught and holding its length constant, an end **1305** of the string is unwrapped until the string is tangent to the surface of the absorber **204**. The path of the end of the string defines a first portion **1302** of the edge ray involute **1301**. At this point, the edge ray involute is equivalent to the standard involute familiar from differential geometry (see, e.g., http://mathworld.wolfram.com/Involute.html).

[0121] Next, the string is extended to include a segment **1304** extending from the end of the unwrapped segment **1306** to an end **1307** which normally intersects (i.e. intersects at right angles to) a line **1303**. The line **1303** extends from an edge point of the entrance aperture **1310** of the concentrator **203** at an angle corresponding to the acceptance angle of the concentrator **203**. The line **1303** corresponds to the wave front of an edge ray of the concentrator **203** (i.e., the ray incident with the maximum acceptance angle of the concentrator).

[0122] The extended string has the form of a taught string which extends around a push pin placed at the end of the unwrapped segment **1302** to the line **1303**. The end **1307** of the string is allowed to slide (frictionlessly) along line **1303** while maintaining the normal orientation of segment **1304** to the line **1303**. Thus, as the end **1307** slides with the string kept taught, the position of the push pin is adjusted to maintain the normal orientation of segment **1304** to line **1303**. The path of push pin continues to trace out the remaining portion **1308** of the edge ray involute.

[0123] As the slope of the involute defined by the movement of push pin increases towards infinity, the process is stopped, and one half of the reflective surface **701** of concentrator **203** has been defined. The remainder of the surface may be obtained by reflection in the optic plane of the concentrator **203**. Alternatively, the process may be ended before the slope approaches infinity to produce a truncated design (e.g., in cases where material costs, weight, or other considerations preclude full extension of the reflective surface).

[0124] Not wishing to be bound by theory, using the framework of the Hottel string method familiar from thermodynamics (see, e.g., Hoyt C. Hottel, Radiant-Heat Transmission 1954, Chapter 4 in William H. McAdams (ed.), Heat Transmission, 3rd ed. McGraw-Hill), which is herein incorporated by reference in its entirety, it can be shown that the above described string-based design method will result in a concentrator design which operates at the thermodynamic limit. As will be apparent to one skilled in the art, the method may be easily adapted to absorbers having other cross sectional shapes, including square shapes, round shapes, irregular shapes, etc. Further, the design method may be used, in some cases, for example flat absorbers to obtain three dimensional concentrators by rotation of the two dimensional solution about the optic axis.

[0125] The design method described above may be implemented as software on a computer. The output of the design method software may be, e.g., a data file, an image, a print out, etc. The output of the design method software may control one or more automated fabrication tools to fabricate a concentrator. The designs may be evaluated and/or optimized using optical design tools, e.g., including ray tracing applications and other optical design applications know in the art.

[0126] The string method described above will necessarily result in a design where the active surface of the absorber **204** is in contact with the reflective surface **701** of the concentrator **203** at one or more points. In practice, it may be impossible to meet this condition. For example, as described above, the active surface of an absorber **204** may be a selective surface **405** located within an evacuated enclosure **401**. The presence of the enclosure **401** requires a gap between the selective surface **405** and the reflective surface **701** of the concentrator **203**. Such a gap will result in a design which does not operate at the thermodynamic limit (i.e., the shape factor from the active surface of the absorber **204** may be less than one or some light incident on the concentrator may miss the absorber).

[0127] The following presents techniques for providing advantageous concentrator designs which take into account

an absorber/concentrator gap. Consider a linear (2-D) nonimaging concentrator. In the absence of dielectric materials (no refraction) the angular acceptance is an ellipse in direction cosines with semi axes $\sin(\theta_0)$ and 1. For the current model, this phase space ellipse is considered uniformly populated in a Lambertian sense. Then the maximum flux concentration C_o is $1/\sin(\theta_0)$ and the maximum irradiance on the absorber is $I_0/\sin(\theta_0)$ (all material losses, etc are neglected). I_0 is the irradiance on the aperture.

[0128] As noted above, idealized designs have no geometrical losses, the reflectors touch the absorber, one simply chooses $C \sim C_0$ (or less, e.g., to save material via truncation) and the design is determined. But in a practical design, the reflector cannot touch the absorber (resulting in a gap) and C is not necessarily $\sim C_0$, it can be smaller or larger. The following describes a method of making design choices which result in an advantageous concentrator design even in the presence of a concentrator/absorber gap.

[0129] Solar collector performance can be modeled as:

$$Q_{out}=\eta_0 Q_{in}-Q_{loss}$$

[0130] where η_0 is the optical efficiency, Q_{in} is the insolation (I) multiplied by the aperture area (A) and Q_{loss} is a function of T (absorber temperature), T_A (ambient temperature) and perhaps some other factors. For evacuated receivers, Q_{loss} is to an excellent approximation $A_{abs} \in \sigma(T^4-T_A^4)$ where A_{abs} is the absorber area, $\in$ is the emissivity and $\sigma=5.67\times10^{-8}$ in MKS units. Then the operating efficiency

$$\eta=Q_{out}/Q_{in}=\eta_0-Q_{loss}/Q_{in}=\eta_0-[A_{abs}/A]f(T,T_A)/I$$

[0131] Since $A/A_{abs}=C$, the

[0132] geometrical

[0133] concentration

$$\eta=\eta_0-[1/C]f(T,T_A)/I.$$

[0134] Accordingly, the design procedure involves maximizing η by appropriately selecting η_0 and C. Several approaches are available for accommodating a gap between absorber and reflector. Referring to FIG. **14**A, one approach is to surround the physical absorber **204** by a virtual absorber **1401** which contacts the reflective surface **701** of the concentrator **203**. The virtual absorber **1401** has virtual absorber area A'_{abs}. Then η_0 rescales as

$$\eta_0=(A_{abs}/A'_{abs})\eta_0$$

as follows from reciprocity and the view factor from A_{abs} to $A'_{abs}=1$. Designing for

$$A'_{abs}/A=\sin(\theta)=1/C_0 \text{ while } A_{abs}/A=1/C \text{ gives}$$

$$\eta=\eta_0'-[1/C]f(T,T_A)/I=$$

$$(A_{abs}/A'_{abs})\eta_0-(A_{abs}/A)f(T,T_A)/I=$$

$$(C)\eta_0-(A_{abs}/A'_{abs})(A'_{abs}/A)f(T,T_A)/I=$$

$$(A_{abs}/A'_{abs})\eta_0-(A_{abs}/A'_{abs})(1/C)f(T,T_A)/I=$$

$$(A_{abs}/A'_{abs})[\eta_0-(\sin(\theta)f(T,T_A)/I].$$

[0135] Note C has been replaced by $1/\sin(\theta)$. Note that, in practice there is usually some truncation to save reflector material, so C may be less.

[0136] Accordingly, a reflector design may be optimized by making A'_{abs}/A_{abs} approach 1, e.g., as shown in FIG. **14**B. Once this optimum virtual absorber shape has been determined, the shape of the concentrator may be obtained, e.g., using the string method described above with the virtual absorber **1401** in place of the actual absorber **204**.

[0137] Note that

$$Q_{out}=A\eta=(CA_{abs})[\eta_0-(\sin(\theta)f(T,T_A)/I]=[A_{abs}/\sin(\theta)][\eta_0-(\sin(\theta)f(T,T_A)/I]$$

is independent of A'_{abs}. That is, the absorber has the maximum irradiance allowed by thermodynamics (second law). For additional background on the use of virtual absorbers in concentrator design, see R. Winston, Ideal Flux Concentrators with Reflector Gaps, Applied Optics 17, 1668 (1978), which is incorporated by reference in its entirety.

[0138] Another approach to dealing with a concentrator/absorber gap is to immerse the absorber in a cavity. See, e.g., R. Winston, Cavity Enhancement by Controlled Directional Scattering, Appl. Opt. 19, 195 (1980), which is incorporated by reference in its entirety.

[0139] In this case η_0 is essentially unchanged, but C is significantly reduced. This gives $\eta=\eta_0-[1/C]\, f(T, T_A)/I$ and there is the possibility of trading off η_0 against C. In other words, one can only partially immerse the absorber in the cavity, thereby incurring some loss, but restore some of the lost C in the concentrator design. This tradeoff is temperature dependent; and typically it is more advantageous to increase C when the temperature is high.

[0140] The cavity design may take a variety of forms, e.g., single or multiple V-shaped grooves or W-shaped grooves. There is a natural upper bound for the groove design in a cylindrical absorber, where the gap distance between the absorber and the concentrator is equal to the radius of the absorber. In the trade-off between concentration and gap loss, the engineering optimum is neither extreme but rather some intermediate choice between a fully cavity immersed absorber, and no cavity at all (i.e., a design based on the virtual absorber technique described above). As shown in FIG. **16**, in typical embodiments the concentration increases linearly with gap size, but the gap loss only increases quadratically, thereby favoring partial immersion. Note the gap loss calculated by our thermodynamic (string) method is the average over the acceptance angle. The loss at a particular angle may vary and is typically greatest at zero angle, and substantially zero near the angle of acceptance.

[0141] For example, referring to FIG. **15**A, trough shaped concentrator **203** features a V-shaped cavity portion **1501** running along the bottom of the trough and providing partial immersion of the cylindrical absorber **204**. The shape of the remaining portion **1502** of the trough is determined, e.g., using the virtual absorber and string method described above. As shown, the design is characterized by a virtual to physical absorber ratio of $A'_{abs}/A_{abs}=0.92$ and a gap loss of 0.01.

[0142] Appendix 1 includes an exemplary algorithm script written in the well known Scilab scientific computing environment (available at "http://www.scilab.org") for designing a concentrator of the type described above. As will be understood by those skilled in the art, this particular exemplary algorithm may be modified or extended based on particular design requirements.

[0143] In other embodiments, other suitable values for A'_{abs}/A_{abs} and gap loss may be chosen. In general, once these values are selected, one is still left with the choice of cavity parameters, e.g., choosing the coordinates of the V-shaped cavity aperture and the opening half angle α of the V. In some embodiments, a large opening angle (i.e. a shallow V) is favorable to minimize material used.

[0144] The following describes an exemplary method for determining the cavity parameters. Referring to FIG. **15**B, a cylindrical absorber **204** of radius r is centered at the origin. One locates the center (O_x, O_y) of the image **1504** of the cylindrical absorber which would be formed if the reflective V-shaped cavity is extended as shown (indicated with a dotted line), so that the top of the image circle is even with or slightly above the aperture of the cavity. Based on this requirement, the end points of the cavity aperture may be determined. For example, a Scilab script shown in Appendix 1 may be used to determine the position of the end points in an exemplary embodiment. Here, the end points are at coordinates x=+/−0.48, y=−1.25. The final step in determining the cavity parameters is to determine y_{min}. The opening half angle α of the V-shaped cavity and y_{min} are related by $\tan(\alpha)=x/(y-y_{min})$. Further, it can be shown that $O_y=2\,y_{min}\sin^2\alpha$.

[0145] Based on these relations, one can calculate a table of possible values of y_{min}, α, O_y, $(y-O_y)$ and compare with r to find a reasonable solution. Table 1 below is an exemplary table of values for the design shown in FIGS. **15**A-**15**B. In this case, with r=1.05, one sees that $y_{min}=-1.52$ is a reasonable choice.

TABLE 1

y_{min}	α	O_y	$(y-O_y)$
−1.6	53.7	−2.08	−0.83
−1.54	58.8	−2.25	−1.10
−1.53	59.6	−2.28	−1.03
−1.52	60.5	−2.30	−1.05
−1.50	62.3	−2.35	−1.30
−1.40	72.6	−2.55	−1.30

[0146] Although the specific examples described above have dealt with concentrating radiation to an absorber to generate heat, it is to be understood that in various embodiments the absorber may be a transducer which converts solar light to another form of energy. For example, the absorber may include photovoltaic material which generates electricity in response to incident light. In some embodiments, the absorber may transform incident light into multiple different forms of energy, e.g., electricity and heat. For example, U.S. Provisional Patent Ser. No. 61/378,301, filed Aug. 30, 2010, the entire contents of which are incorporated herein by reference, describes absorbers which include PV material and selective thermal absorbers.

[0147] In contrast to conventional optical design, the solar concentrators of this disclosure are designed from the principles of thermodynamics, and in particular the second law. TdS=dE+PdV is arguably the most important equation in Science. If we were asked to predict what currently accepted principle would be valid 1,000 years from now, the Second Law of thermodynamics would be a good bet. From this we can derive entropic forces: F=T grad S, The Stefan-Boltzmann radiation law (const. T^4), Information theory (Shannon, Gabor), Accelerated expansion of the Universe, and even Gravity. We can illustrate the Failure of conventional optics by a thought experiment; small bodies A, B at foci of an ellipse as shown in FIG. **17**A. A portion of the ellipse is replaced by a sphere centered at A.

[0148] It appears that FAB<<FBA where FAB is the probability of radiation starting at A reaching B - - - etc so A would heat up at the expense of B cooling down, but that violates the second law.

[0149] To understand these things it is best to start with the theory of furnaces. We start with a three wall furnace shown in FIG. **17**B. Fij are probabilities of radiation from wall i reaching wall j. As there are 6 unknown Fij, six equations are needed. Three come from energy conservation, and 3 from the second law. The results follow readily from inspection.

$$F12=(A1+A2-A3)/(2A1)$$

$$F13=(A1+A3-A2)/(2A1)$$

$$F23=(A2+A3-A1)/(2A2)$$

[0150] where A1, A2, A3 are the three sides shown in FIG. **17**B.

[0151] FIG. **17**C shows a 4-wall enclosure, which is a configuration of greater interest. The 4-wall enclosure readily reduces to two 3-wall enclosures so that we can apply the above formula.

$$F14=[(A5+A6)-(A2+A3)]/(2A1)$$

$$F23=[(A5+A6)-(A1+A4)]/(2A2).$$

[0152] Turning to FIG. **17**D, there is shown a schematic view of a radiation source **1700**, an aperture **1702** and an absorber **1704** that includes a general convex or flat shape. A number of parameters of the absorber and aperture will be shown and now explained for optimal operation and for manufacturing. The present disclosure includes a convex or flat shape that provides a high probability that the solar radiation will concentrate at a preselected portion to capture as much solar radiation as possible. As can be seen a number of relationships are established between the radiation source, the aperture and the absorber as shown by 1, 2, 3. Suppose the radiation source 1 (example the sun) is maintained at temperature T1. Then the temperature of the absorber 3 will reach T1 if and only if F31=1.

[0153] Proof: $q\ 13=\sigma T1^{*4}A1F13=\sigma T1^{*4}A3F31$, where qij is the radiation transfer from i to j.

[0154] But $q3total=\sigma T3^{*4}A3\geq q13$ at steady state.

[0155] $T3\leq T1$ (second law)→F31=1 if and only if T3=T1.

[0156] The first law of thermodynamics (energy conservation) allows q12=q13 which implies F12=F13 for a maximally efficient concentrator. Define the geometric concentration C=A2/A3. The second law requires A1F13=A3F31. Then F12=F13 implies A1F12=A3F31. This implies A3F31 is constant independent of the optical design. C is maximum when A3 is minimum which implies F31 is maximum=1. Again we find that the combination of maximum concentration and maximum efficiency requires F31=1. We can think of this as maximum thermodynamic efficiency. F31=1 also provides an important relation for concentration because A3=A1F12 but A1F12=A2F21 by the second law. It follows that Cmax=1/F21 which expresses maximum concentration as the reciprocal of the probability that radiation from the concentrator aperture (A2) regarded as a black body would reach the source A1.

[0157] An important case is the source 1 at ∞ (example very far away, like the sun). Suppose we wish to efficiently concentrate energy from a range of sun angles+/−Θ, for example, a range of angles sufficient to substantially include the solar angles during the year so that tracking is not needed. Mathematically the measure of far away is set by the dimension of A2 (L2) so that far means d>>L2, where d is the distance between 1 and 2. As d approaches ∞ the strings become parallel.

$$\text{Long String}-\text{Short string}=S1-S2=L2\sin\Theta.$$

[0158] F21 approaches sin Θ.

[0159] Notice Θ is the maximum angle of radiation incident on A2. Cmax=1/sin Θ.

[0160] As the distance approaches infinity, the sun's rays appear almost parallel to one another. Therefore, as we approach infinity, F21 is equal to sin Θ, where Θ is equal to the angle of the essentially parallel sun's rays at one sun angle with respect to the axis as shown in FIG. **18**. Therefore, Cmax=1/sin Θ and note that in this embodiment, the maximum angle on A2 is Θ. For three dimensions,

$$F21=(S1-S2^2/L2^2),$$

[0161] where L2 is the diameter of A2. As we approach infinity, F21 is equal to sine Θ^2.

[0162] Therefore Cmax=1/sin^2 Θ, another example of the principle that maximum concentration is the reciprocal of the probability that radiation from the concentrator aperture regarded as a black body would reach the source.

[0163] Another way to obtain the sine law is to consider the angular momentum with respect to the axis of symmetry shown in FIG. **20**. The optical momentum is P=n(L, M, N), where n is the index of refraction and L, M, N are the direction cosines of the rays and the maximum angular momentum at the entrance A2 of the concentrator is J=(L2/2) sin Θ, and at the exit A3 the maximum value of J is L3/2, where L3 is the diameter of A3. Since J is conserved, the maximum concentration is (L2/L3)^2=1/sin^2 Θ. For simplicity we have assumed n=1 in this example.

[0164] In another embodiment of the present disclosure, the present invention may be used in a water desalination and purification plant that removes salt from various types of water sources including sea water, brackish water etc. with the objective of providing fresh water for every day consumer use. There are two main types of desalination technologies that are most prevalent today. The most common are various distillation processes that require high temperatures for operation. The second type is reverse osmosis, which requires high pressure to drive pure water through a membrane separation process. Water purification focuses more on the removal of various particulate, organic and inorganic impurities from existing fresh water supplies or when attempting to implement water reclamation projects.

[0165] In another embodiment of the present disclosure, the solar array may include a reflective surface that is a Compound Parabolic Concentrator (CPC). For example, the reflective surface may include a two dimension compact parabolic concentrator that is an ideal concentrator, i.e., it works perfectly for all rays within the acceptance angle q, and rotating the profile about the axis of symmetry gives the 3-D CPC. The 3-D CPC is very close to ideal reflective surface.

[0166] In another embodiment of the present disclosure, the solar array may also include Collimator for a Tubular Light Source. The collimator may include a predetermined shape on each side of the tubular light source to collect the light in a predetermined location as discussed.

[0167] Although the specific examples described above have dealt with concentrating radiation from a relatively large solid angle of incidence onto a relatively small target (e.g. concentrating solar light onto an absorber), it will be understood that they may equally well be applied to broadcasting radiation from a relatively small source to a relatively large solid angle (e.g. collecting light from an LED chip to form a beam or sheet of light). The small source may, for example, include a light emitting diode, an organic light emitting diode, a laser, or a lamp.

[0168] Although a number of exemplary light concentrators have been described, in various embodiments, any other suitable concentrator may be used. For example, in some embodiments, non-imaging concentrators of the type described in Roland Winston et al, Nonimaging Optics, Academic Press (Elsevier, 2005) may be used, including concentrator designed using the edge ray principle as described therein. In various embodiments concentrators may include reflective, refraction, diffractive or other elements. In some embodiments, at least a portion of the concentrator may reflect light by total internal reflection.

[0169] One or more or any part thereof of the techniques described herein can be implemented in computer hardware or software, or a combination of both. The methods can be implemented in computer programs using standard programming techniques following the method and figures described herein. Program code is applied to input data to perform the functions described herein and generate output information. The output information is applied to one or more output devices such as a display monitor. Each program may be implemented in a high level procedural or object oriented programming language to communicate with a computer system. However, the programs can be implemented in assembly or machine language, if desired. In any case, the language can be a compiled or interpreted language. Moreover, the program can run on dedicated integrated circuits preprogrammed for that purpose.

[0170] Each such computer program is preferably stored on a storage medium or device (e.g., ROM or magnetic diskette) readable by a general or special purpose programmable computer, for configuring and operating the computer when the storage media or device is read by the computer to perform the procedures described herein. The computer program can also reside in cache or main memory during program execution. The analysis method can also be implemented as a computer-readable storage medium, configured with a computer program, where the storage medium so configured causes a computer to operate in a specific and predefined manner to perform the functions described herein.

[0171] A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention.

[0172] As used herein the term "light" and related terms (e.g. "optical") are to be understood to include electromagnetic radiation both within and outside of the visible spectrum, including, for example, ultraviolet and infrared radiation.

[0173] As will be understood by one skilled in the art, for any and all purposes, particularly in terms of providing a written description, all ranges disclosed herein also encompass any and all possible subranges and combinations of subranges thereof. Any listed range can be easily recognized as sufficiently describing and enabling the same range being broken down into at least equal halves, thirds, quarters, fifths, tenths, etc. As a non-limiting example, each range discussed herein can be readily broken down into a lower third, middle third and upper third, etc. As will also be understood by one skilled in the art all language such as "up to," "at least," "greater than," "less than," and the like include the number recited and refer to ranges which can be subsequently broken down into subranges as discussed above.

[0174] Definitions that are contained in text incorporated by reference are excluded to the extent that they contradict definitions in this disclosure. For the purposes of this disclosure and unless otherwise specified, "a" or "an" means "one or more."

[0175] As used herein, the term "comprising" is intended to mean that the compositions and methods include the recited elements, but not excluding others. "Consisting essentially of" when used to define compositions and methods, shall mean excluding other elements of any essential significance to the combination for that intended purpose. "Consisting of" shall mean excluding more than trace elements of other ingredients and substantial method steps for making or using the concentrators or articles of this invention.

[0176] The construction and arrangements of the solar energy concentrator, as shown in the various exemplary embodiments, are illustrative only. Although only a few embodiments have been described in detail in this disclosure, many modifications are possible (example, variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.) without materially departing from the novel teachings and advantages of the subject matter described herein. Some elements shown as integrally formed may be constructed of multiple parts or elements, the position of elements may be reversed or otherwise varied, and the nature or number of discrete elements or positions may be altered or varied. The order or sequence of any process, logical algorithm, or method steps may be varied or re-sequenced according to alternative embodiments. Other substitutions, modifications, changes and omissions may also be made in the design, operating conditions and arrangement of the various exemplary embodiments without departing from the scope of the present disclosure.

[0177] Having thus described several aspects of at least one embodiment of this invention, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

APPENDIX 1

```
%Mind the Gap Version 2
N0=1000;
N1=100;
N2=1000;
%Define parameters
R=1.05; %10.5mm
R1=1.35; % 13.5mm
D1=2.7; %27mm
theta=(2*pi/360)*(40); %40deg
phi=(2*pi/360)* 14; %14deg
psi=(pi/2)+theta;
scale=1.0;
%-------------------------------------------------------------------------------
L1 =scale*pi*R*
(1/(sin(theta)^2)+((cot(theta))^2)*(1/(sin(theta))+1)^2)^(1/2);
inc=(L 1 +3 * R)/N2;
L=(5*R*pi/2)+(R*(theta-2*phi))+L1;
%-------------------------------------------------------------------------------
X0=R*sin(psi)-L1 *sin(theta);
Y0=-R*cos(psi)+Ll *cos(theta);
%-------------------------------------------------------------------------------
```

APPENDIX 1-continued

```
%profile for involution
gamma=(psi-phi)/N1;
s1=(psi-phi)*R;
xi(1)=R*cos(theta)+s1*sin(theta);
yi(1)=R* sin(theta)-s1*cos(theta);
xl(l)=-xi(l);
rho(1)=sqrt(xi(1)^2+yi(1)^2);
n=l;
while (rho>=Rl);
    sn=s1 -R*((n-1)*gamma);
    xi(n)=R*cos(theta-(n-1)*gamma)+sn*sin(theta-(n-1)*gamma);
    yi(n)=R* sin(theta-(n-1)*gamma)-sn*cos(theta-(n-1)*gamma);
    xl(n)=-xi(n);
    rho=sqrt(xi(n)^2+yi(n)^2)
    n=n+l
    %vee
    a=-xi(n-l);
    b=yi(n-l);
end;
%Vee
c=-1.54; %ymin
x6(l)=-a
y6(l)=b
x6(2)=0;
y6(2)=c;
x6(3)=a;
y6(3)=b;
%-------------------------------------------------------------
%profile for one reflection
flag=0;
i=0;
s=(2*cos(theta)/N0)*(L1* sin(theta)-R*sin(psi));
%-------------------------------------------------------------
for n=l:N0;
    i=0; flag=0;
    xn=((n-1)*s)/cos(theta)+x0;
    Lt=L-((n-1)*s*tan(theta));
    %-------------------------------------------------------
    while(flag==0)
    i=i+l;
    sL=i*inc;
    xtn=sL*sin(theta)+xn;
    ytn=y0-sL*cos(theta);
    %-------------------------------------------------------
    Rt=(xtn^2+ytn^2)^(l/2);
    betal=asin(ytn/Rt);
    beta2=acos(R/Rt);
    %-------------------------------------------------------
    alpha=(3*pi/2)-(betal+beta2);
    Lt2=sL+(xtn^2+ytn^2-R^2)^(1/2)+R* alpha;
    if((Lt2>=Lt)&(flag==0))
        flag=l;
        x(n)=xtn;
        y(n)=ytn;
        x2(n)=-xtn;
    end;
    end;
end;
d=8.5; %85mm
xt(l)=x(l);
yt(1)=y(1);
xtl(l)=-xt(l);
n=l;
    while (x(n)<=d/2)
    xt(n)=x(n);
    yt(n)=y(n);
    xtl(n)=-x(n);
    n=n+l;
end;
%-------------------------------------------------------------------------------
%absorber circle profile
for j=l:100;
    angle=(j-l)*2*pi/100;
    x3(j)=R*cos(angle);
    y3(j)=R* sin(angle);
end;
%-----------------------------------------
```

APPENDIX 1-continued

```
%Output values
plot(xi,yi,x1,yi,xt,yt,xt1,yt,x3,y3,x6,y6);
axis equal;
grid;
title('theta=40deg, phi=14deg, R=1.05cm, Rl=1.35cm,
ymin=-1.54cm,d=8.5cm');
c,xi,yi,xt,yt
print,
=====================================================
%maximizes CPC with gap
%r2=rl+gap
%Cmax=1/sin(theta);
%x=C/Cmax;
%y=gap Loss *(C/Cmax);
rl=1.05;
r2=1.35;
z=r2/rl;
alf=acos(rl/r2);
bet=sqrt(z*z-l)-alf;
fi=asin(rl/r2);
psimin=fi;
xmin=(psimin+fi+1/tan(fi))/pi;
xmax=l+bet/pi;
for i=l:10;
      x(i)=xmin+i *(xmax-xmin)/10;
      psi=pi *x(i)-(fi+1/tan(fi));
      y(i)=(fi+l/tan(fi))-(psi+cos(psi)/sin(fi));
      y(i)=y(i)/pi;
end;
xmax
plot(x,y)
axis equal;
grid;
title('Rl=10.5mm,R2=13.5mm,gap=3mm');
print,
```

What is claimed is:

1. An optimized solar concentrator, comprising:

a window for receiving sunlight; and

a tubular absorber, wherein said tubular absorber includes a convex or flat shaped geometry, wherein a distance from a top to a bottom of said convex or flat shaped tubular absorber approaches a predetermined maximum probability to receive and concentrate a maximum amount of said sunlight, said tubular absorber comprising:

a tubular vacuum envelope, said tubular vacuum envelope extending from a proximal end to a distal end along a longitudinal axis;

said tubular absorber obtained by extrusion and made of aluminum or brass;

an outer surface of said tubular absorber facing said outer tubular vacuum envelope includes a selective surface;

said selective surface adapted to absorb said sunlight through said vacuum envelope and convert said sunlight into heat; and

a trough shaped reflector, said trough shaped reflector having at least one reflecting surface extending out from a bottom of said tubular absorber and disposed transverse to said longitudinal axis of said tubular absorber, said reflecting surface having a shape substantially corresponding to an edge ray involute of said tubular absorber.

* * * * *