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(54) **SOLAR-POWERED COOLING AND HEATING SYSTEM USING A STRUCTURED WATER WALL**

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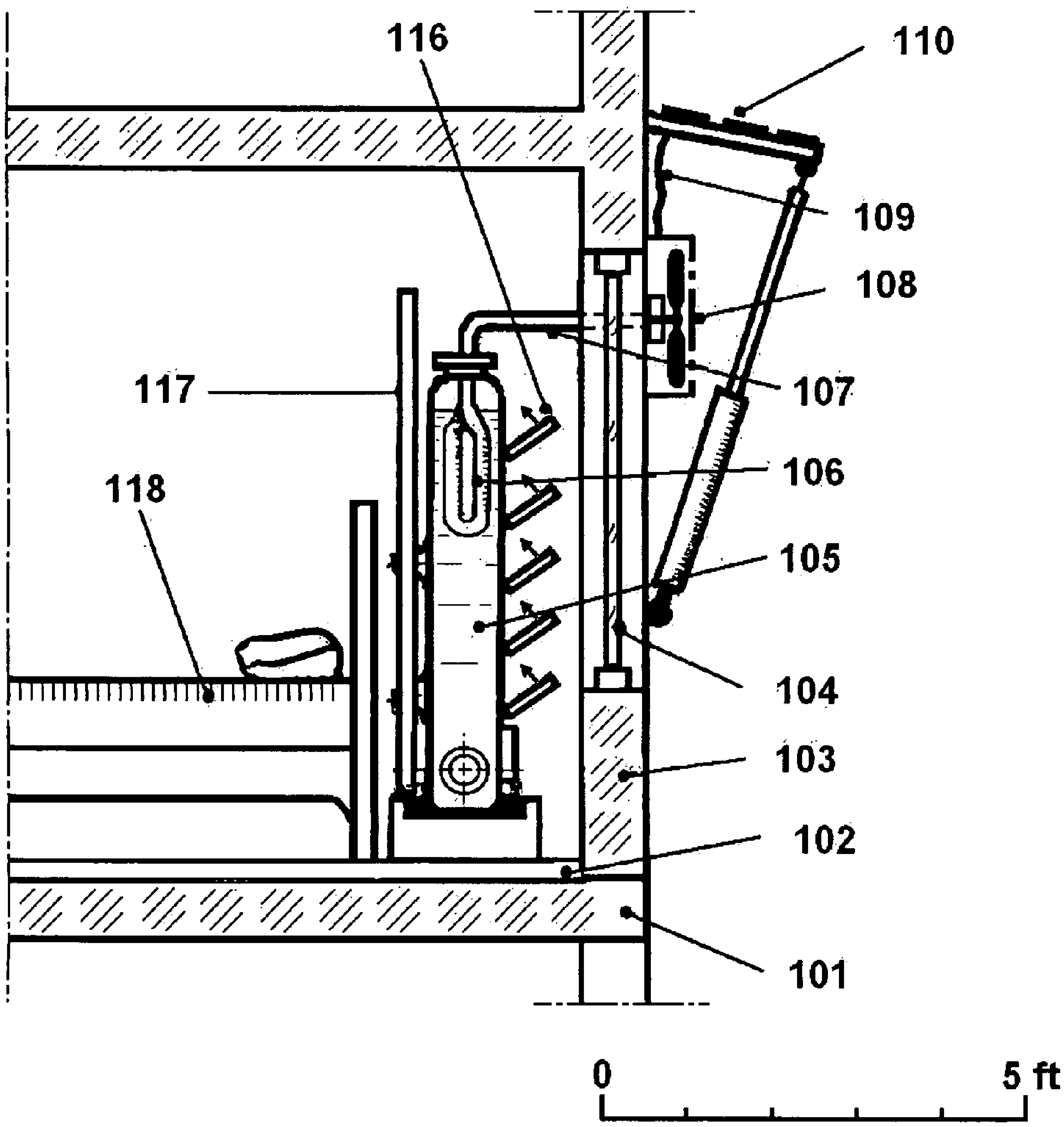
(57) **ABSTRACT**

A solar-powered cooling and heating system comprising one or more vertical water containers of special design as the thermal storage device (the structured water wall), a compressor driven by a DC motor powered directly by solar photovoltaic panel(s) for cooling, and a south-faced window for direct solar heating. The solar photovoltaic panel(s) is placed on an awning above the south-facing window; the said awning is designed to allow full sunlight in the winter but no direct sunlight in the summer through the window. The thermal inertia of the structured water wall allows optimum heating and cooling day and night for all seasons of a year. It allows an automatic self-adjustment utilizing the natural annual and diurnal cycles to achieve maximum comfort and efficiency.



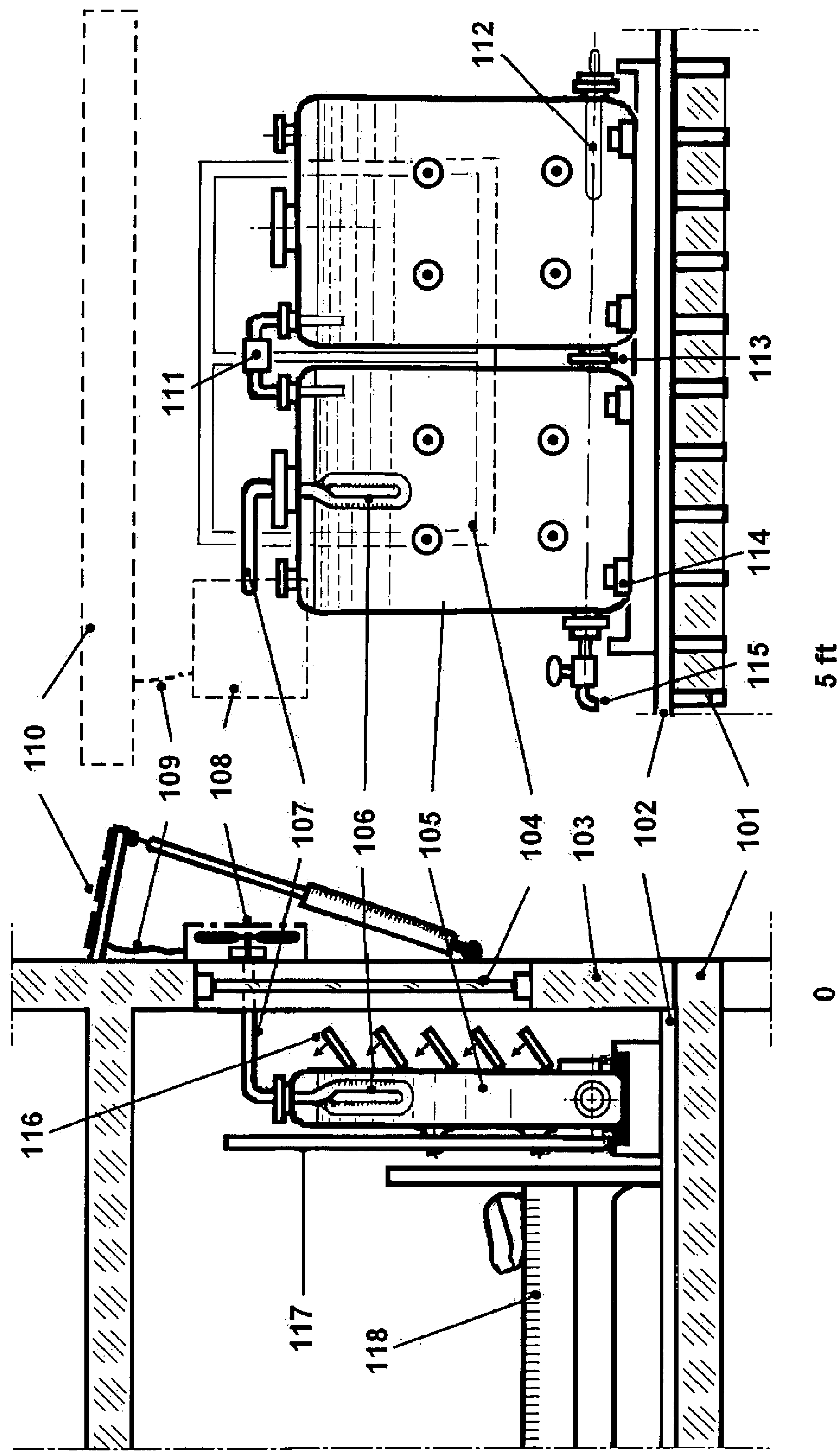

101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
0
5 ft

FIG 1A

FIG 1B

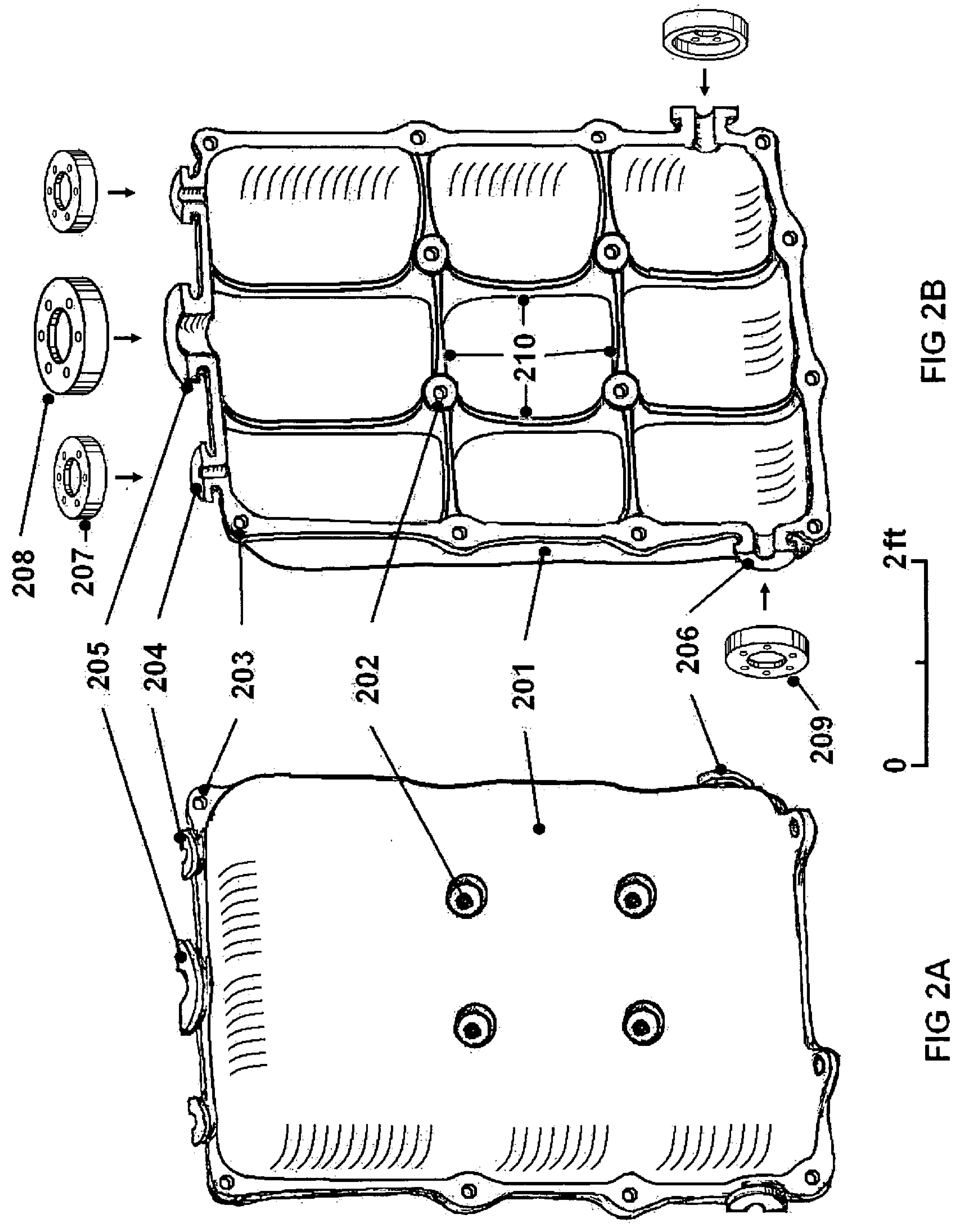


FIG 2A

FIG 2B

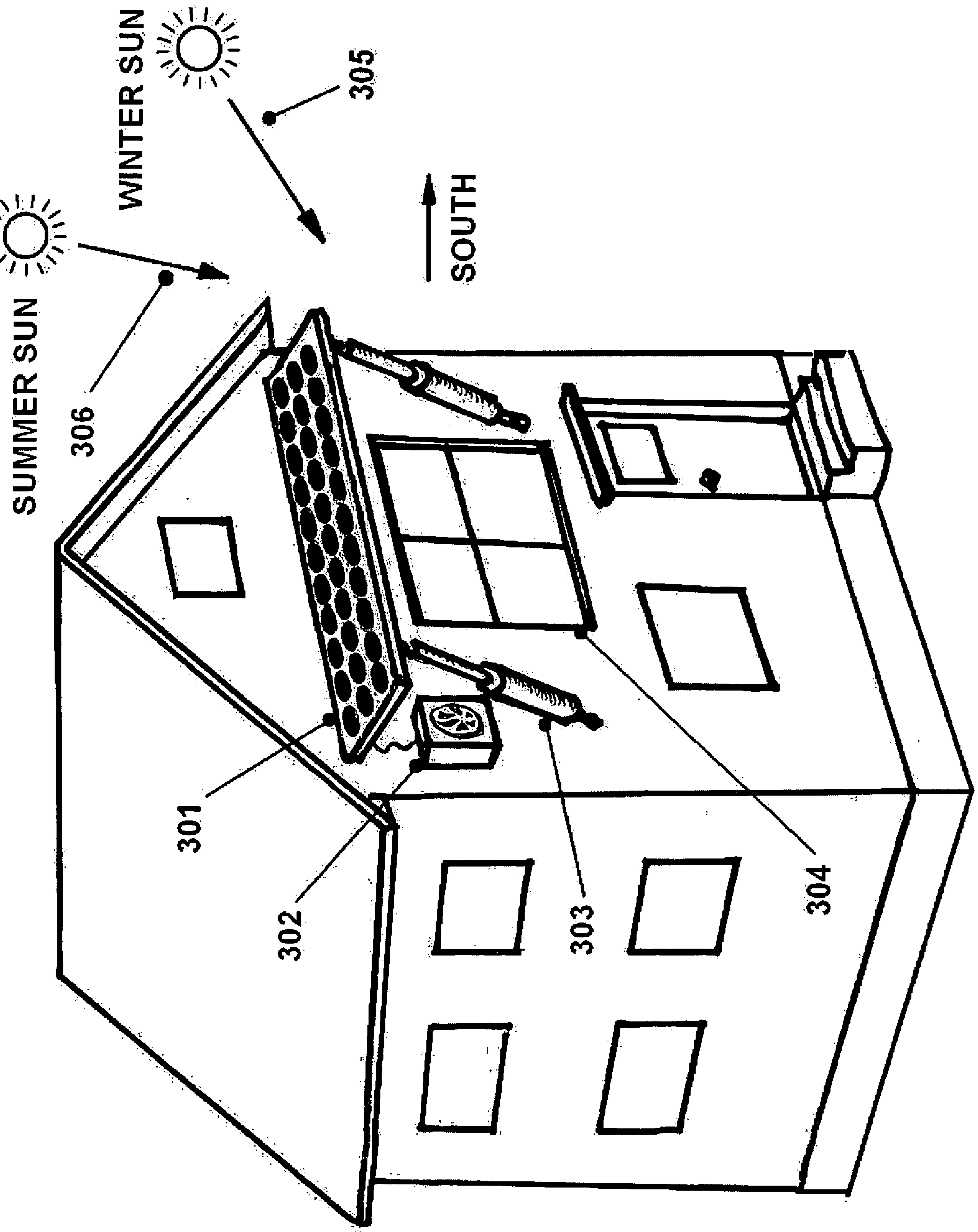


FIG. 3

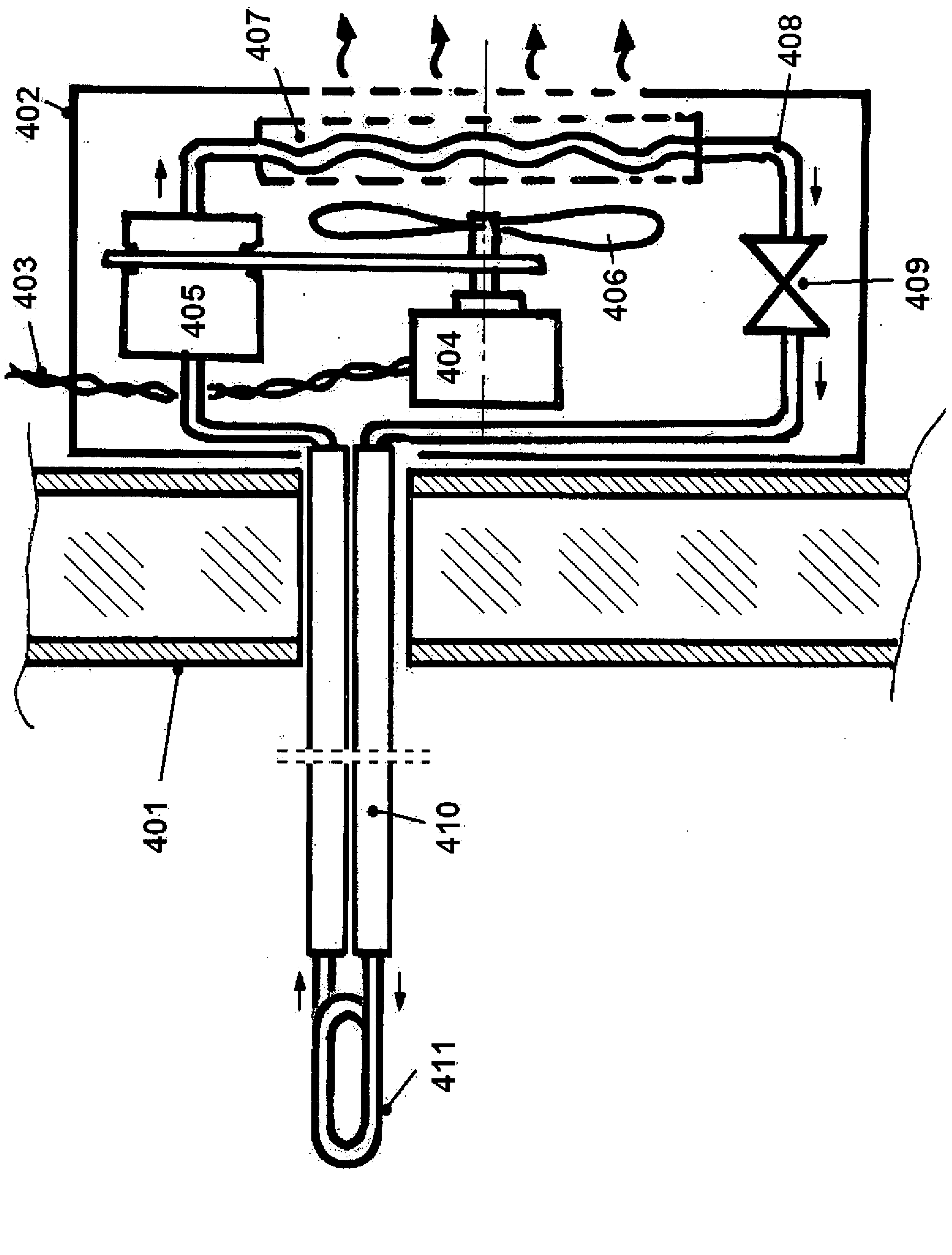


FIG. 4

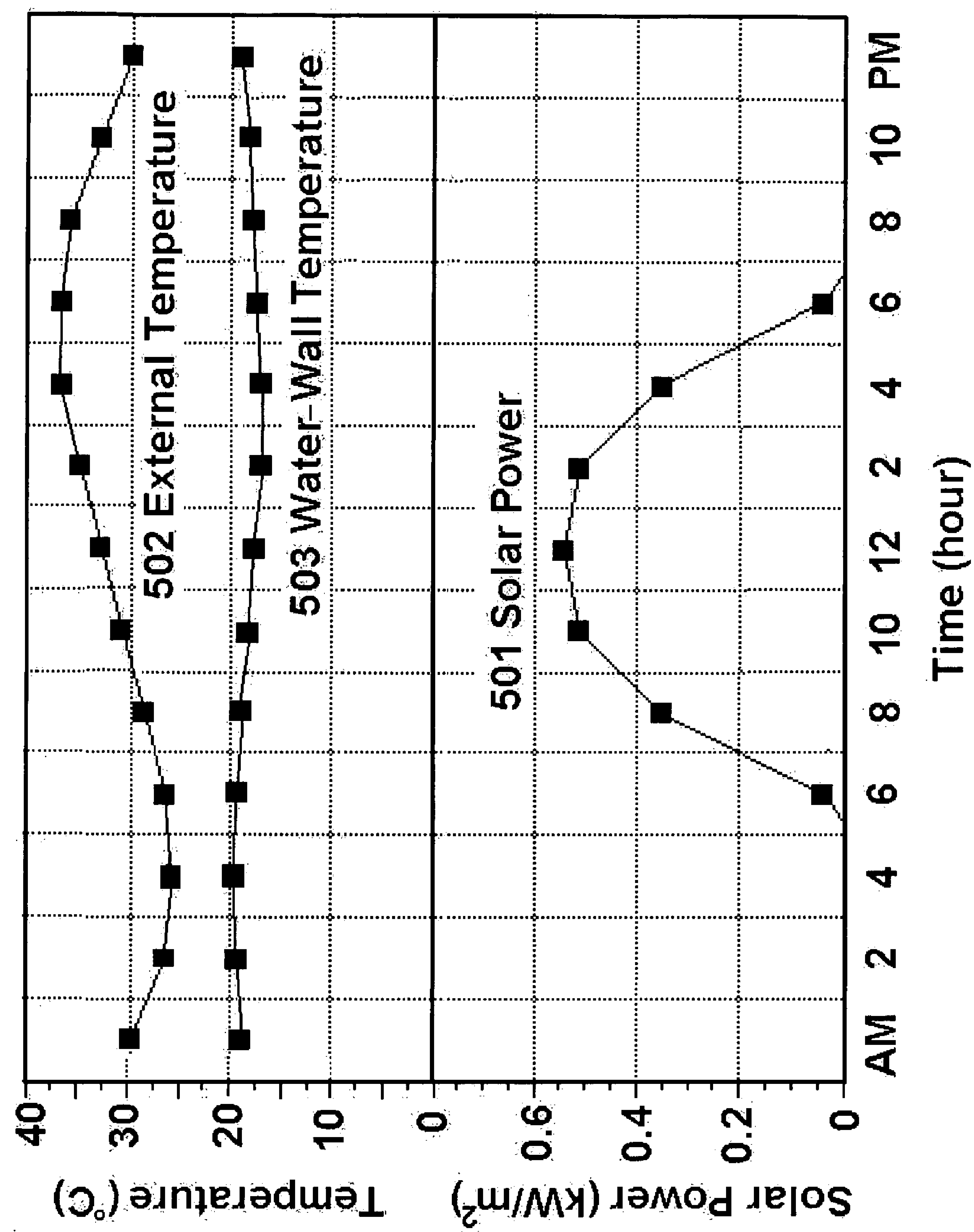

502 External Temperature
503 Water-Wall Temperature
501 Solar Power
Temperature (°C)
Solar Power (kW/m2)
Time (hour)
40
30
20
10
0
0.6
0.4
0.2
0
AM
2
4
6
8
10
12
2
4
6
8
10
PM

FIG 5

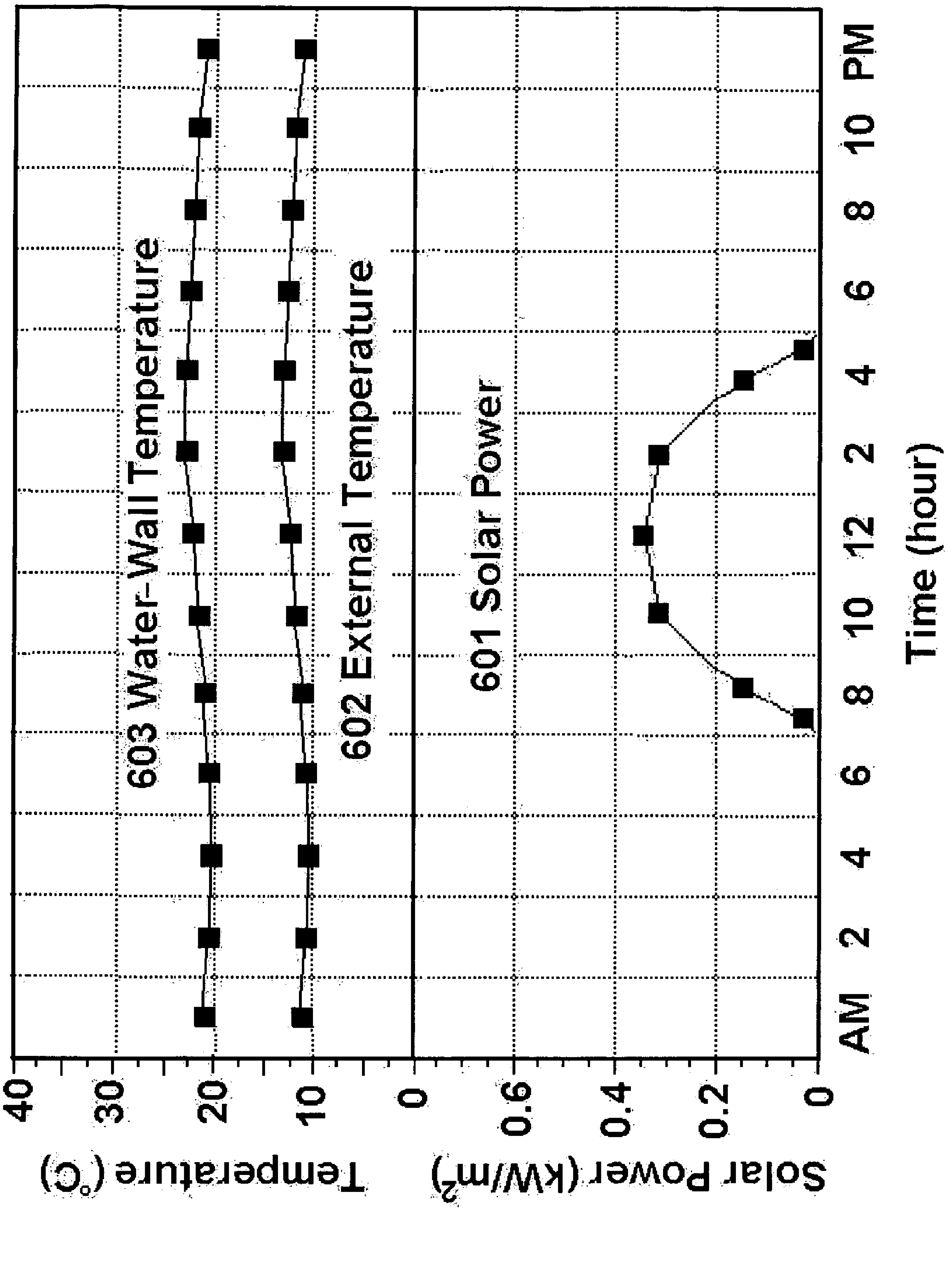

603 Water-Wall Temperature
602 External Temperature
601 Solar Power
Temperature (°C)
Solar Power (kW/m2)
40
30
20
10
0
0.6
0.4
0.2
0
AM
2
4
6
8
10
12
2
4
6
8
10
PM
Time (hour)

FIG 6

SOLAR-POWERED COOLING AND HEATING SYSTEM USING A STRUCTURED WATER WALL

BACKGROUND OF THE INVENTION

[0001] Cooling and heating of buildings, especially residential houses, consume a huge amount of energy worldwide. Because solar energy is directly accessible to a large percentage of the residential houses, using solar energy to cool and heat the houses is highly desirable. For many decades, concepts of cooling and heating systems based on solar energy have been proposed. However, none of those designs has been widely used.

[0002] Several combined solar cooling and heating systems have been disclosed that comprise a solar collector, typically on the roof, to generate hot water (or other liquid) for the storage of thermal energy; then use the stored thermal energy for heating, or for cooling using the heat-pump principle. For example, Worthington in U.S. Pat. No. 4,128,124 (1978); Adcock in U.S. Pat. No. 4,129,177 (1978); Ruder in U.S. Pat. No. 4,153,104; Hiser in U.S. Pat. No. 4,173,994; Yukimachi et al. in U.S. Pat. No. 4,269,263 (1979); Wilson in U.S. Pat. No. 4,674,476 (1987); and Tracy in U.S. Pat. No. 5,941,238 (1999). Those systems are complicated and bulky, having low efficiency because of thermal-storage loss and indirect heating and cooling, requiring dedicated design for new houses substantially different from ordinary houses, and almost impossible to retrofit into existing houses. Those systems have not been widely used in practice.

[0003] A simple idea for solar heating of houses has been practiced using a thermal storage medium, as summarized in E. Marzia's "The Passive Solar Energy Book" (Rodale Press, Emmaus, Pa. 1979); and in D. Chiras's "The Solar House" (Chelsea Green Publishing Company, White River Junction, VM 2002). Typically, masonry thermal storage walls (made of adobe, bricks or concrete) are used as the thermal storage medium. In a sunny winter day, direct sunlight is allowed to come through windows to heat up the masonry wall. The heat stored in the wall is then gradually released after sunset. The temperature of the house or room can be maintained within a comfortable range day and night. However, a masonry wall with sufficient thermal mass is very bulky and heavy which requires a large space and a strong foundation. Therefore, it is not widely used.

[0004] Solar cooling has a similar thermal-storage problem. By directly using the solar energy to drive an air-conditioning unit for cooling the room, it does not provide a relatively constant temperature throughout the entire day and night. Right after sunset, when the environment is still very hot, the cooling effect disappears. And the maximum cooling effect from direct sunlight is at noon time, which is not the hottest time of the day (the hottest time in a day is about 3-5 pm). This problem can be resolved by using a thermal storage medium to store the cooling power generated by solar energy with 4 to 8 hours of delay or inertia. Because generally speaking, the stronger the sunlight in the day time, the more cooling power is required, it can be self-sufficient from day to day.

[0005] However, to store cooling power, a proper design of the thermal storage system must be provided. Masonry walls are not useful as a thermal storage for cooling because of the difficulty to cool it down. It is well known that water is a much better thermal storage medium, as shown in Table 1. To achieve the same thermal mass, the weight of water is only one tenth of that for brick or concrete. Moreover, water has great advantage as storage medium of cooling because of natural convection: once a source of cooling is accessed to the top of a water container, cooling spreads quickly to the entire volume. Although it is well known that water is much more advantageous even for solar heating, the technology and design of reliable and affordable water storage systems does not yet exist. In the field of passive solar heating, most applications utilizing water as thermal storage medium have been using either stacked 55-gallon drums or freestanding metal and plastic cylinders; see the above cited books of E. Marzia and D. D. Chiras. Those systems are cumbersome. Therefore, to date, water storage systems for passive solar heating are not publicly accepted. For solar cooling, to date, water as a cooling storage medium has not been explored.

TABLE 1

Thermal mass per unit weight of different materials

Material	Specific heat (water = 1)	Density (water = 1)	Thermal mass per unit weight (water = 1)
Water	1	1	1
Oak	0.57	0.742	0.768
Adobe	0.24	1.67	0.143
Brick	0.2	1.94	0.103
Concrete	0.156	2.27	0.068

BRIEF SUMMARY OF THE INVENTION

[0006] The current invention discloses a novel apparatus for solar-powered cooling and heating, which comprises one or more water containers of special design to form a structured water wall, placed near a south-faced window in a room as the thermal mass for solar cooling and heating. Using proper design parameters, it could have a thermal inertial delay time of 4 to 8 hours. A solar photovoltaic panel is installed on an awning above the south-faced window. The output of the solar photovoltaic panel is connected directly to a DC motor to drive a compressor of a vapor-compression refrigeration unit. For the principles of vapor-compression refrigeration, see for example W. P. Jones "Air Conditioning Engineering" (Edward Arnold, London 1994). The heat generated by the compressed refrigerant (for example, R22) is dissipated to the surrounding air, and the liquefied refrigerant is then letting into a copper coil through an expansion valve. The copper coil is located near the top of a water container to cool down the water. In a sunny summer day, the electricity generated by the sunlight drives the compressor and cools the water. By natural convection, the entire water wall is being cooled. The temperature of the water wall reaches minimum in the late afternoon, typically 3 pm to 6 pm, which matches the hottest time of the day. Because the structured water wall is located in the room, it cools down the entire room. After sunset, the temperature of the structured water wall gradually increases. Because the environment temperature is also decreasing, the warming up of the water wall is slowing down. The cooling effect persists throughout the night. Such a system has a self-adjusting effect according to the weather: The stronger the sunlight in the day time, the more cooling is generated by the water wall. On the other hand, sunlight could fall on the water wall directly through the window. However, in the summer, the sunlight is blocked by the awnings (which support the solar photovoltaic panels) from coming directly through the window, and the insulating shutters are closed. No heating effect is caused by direct sunlight. In the day time of the winter, by opening the insulating shutters, full sunlight comes through the window and heats up the water wall. In the night, by closing the shutters, the heat is releasing slowly to keep the room warm. In cold and cloudy days, an auxiliary heating system is required. However, substantial savings of the heating cost can be achieved. The said solar-energized cooling-and-heating apparatus can be installed into new houses of standard design, can be retrofit into existing houses, can be decorated as a good-looking furniture (screen, book-shelf, entertainment system, picture-displaying wall, etc.) and can be mass-produced with low cost. The operation of the apparatus is simple and virtually maintenance free.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** shows the solar cooling-and-heating system with a structured water wall.

[0008] FIG. **2** shows the design of the water container.

[0009] FIG. **3** shows an external view of a house with the solar cooling-and-heating system.

[0010] FIG. **4** shows the design of the vapor compression refrigeration system driven directly by solar power through a DC motor and directly connected to a water wall.

[0011] FIG. **5** shows the typical temperature variation of the water wall and the environment in summer time.

[0012] FIG. **6** shows the typical temperature variation of the water wall and the environment in winter time.

DETAILED DESCRIPTION OF THE INVENTION

[0013] FIG. **1** shows a design of the apparatus in a residential building. The wooden beams, **101**, typically 2 by 10 with 12 to 18 inch spacing, support the floor **102**. The external wall **103** is insulated and with a window **104**. In the room, about 1 ft from the window, is a structured water wall **105**. In this example, the structured water wall comprises two vertical water containers. A cooling coil **106** directs the expanding refrigerant through the pipes **107** from the refrigerating unit **108**, which is driven by a DC motor connected through wire **109** to the solar photovoltaic panel **110**, located outside the wall **103** on an awning above the window **104**. The two water containers are connected from the top through a pump **111**, which is also driven by a DC motor powered by the solar photovoltaic panel **110**. An optional heating element **112** is installed through a flange to heat up the water wall if needed. Near the bottom of the two water containers, a flange **113** connects them to provide water flow. The structured water wall is installed on a base, typically made of wood, through the bolts **114**. A valve **115** is connected to one of the water containers for draining the water if necessary.

[0014] In front of the structured water wall **105**, insulating shutters **116** are installed. The shutters are preferably made of plastic foam, about one inch thick, and covered by aluminum foil or colored white. During the summer, the shutters are closed to become a continuous thermal insulating panel to the water wall, to avoid thermal loss through the window. During the day time of winter, the shutters are opened to an angle approximately equal to the inclination angle of the sunlight. The surface of the structured water wall is colored black to ensure good absorption of heat. After sunset, the shutters are closed. This can be controlled by a timing device or a light-sensing device. The back side of the water wall is protected by a panel **117**, which is decorated as a screen in this case. Also in the room, a bed **118** is placed nearby. The panel **117** can also be decorated as an entertainment center or a bookcase as appropriate.

[0015] To facilitate mass production, the preferred design of the water container comprises two identical halves, as shown in FIG. **2**. It can be made of cast aluminum or glass-fiber reinforced plastics. It can be formed using a pair of simple moulds. To reduce weight and manufacturing cost, the body **201** has non-uniform thickness: the container wall is thicker near the bottom and thinner near the top. In the middle of the container, four or more through holes **202** facilitates the use of steel bolts to reinforce the structure. At the edges, 10 holes **203** are made for bolts. On the top of the container, there are two small flanges **204** for interconnection through the pump **111** or filling with water, and one large flange **205** for the cooling elements **106**. Near the bottom, there are two small flanges **209** for interconnecting the containers and for the drainage of water. After the two halves are bonded together with water-resistant glue and bolts, the flanges are further covered by caps **207**, **208**, and **209**. To ensure good absorption of sunlight in the winter, the front side is painted black.

[0016] FIG. **3** shows the external view of the house with such an apparatus. The solar photovoltaic panel **301** is installed as an awning facing south on supports **303**. The refrigeration unit **302** (see FIG. **4** for details) is located in a cool location. The geometry of the awning **301** is designed such that it allows full sunlight to enter the window **304** in the winter, **305**; and prevents any direct sunlight to enter window **304** in the summer, **306**.

[0017] FIG. **4** shows the details of the vapor-compression refrigeration system driven by solar power through a DC motor. For a general description of the vapor-compression refrigeration system, see W. P. Jones 1994. In FIG. **4**, **401** is the wall of the house. The refrigeration unit **402** is mounted on the external of the house. A cable **403** leads the electric current from of the solar photovoltaic cells to a DC motor **404**. The motor drives both the compressor **405** and the fan **406**. Compressor **405** compresses the refrigerant vapor into the condenser **407**. After the heat is released into the air by fan **406**, the refrigerant is liquidized then flows to an expansion valve **409** through pipe **408**. The vapor of the refrigerant flows through an insulated pipe **401** into the heat exchange coil **411**. Directly from the factory, the pipe **410** is straight. During the installation of the apparatus, the pipe is let through the hole of the wall **410** into the interior of the house. Then the pipe is bent such that the heat exchange coil **411** reaches the top of the water in the container through the flange **205**.

[0018] The operation of the apparatus is as follows. In a sunny day of summer, the solar photovoltaic panels **110** receive plenty of sunlight to generate electricity. Through the DC motor **404**, it directly drives the compressor **405** of the refrigerating unit. The refrigerant, for example R22, is compressed, and the heat generated is dissipated to the environment by the fan **406**. The refrigerant is then liquefied. It passes through an expansion valve **409** to become vapor, and then flows through pipe **410** to the heat exchange coil **411** near the top of the water wall **105**. If there is a single water container, the cooling effect spreads quickly to the entire volume by convection. For systems having two or more water containers, see FIG. **1**, a pump driven by the electricity from the solar panel **111** provides circulation of the water, and the cooling effect spreads to all the water containers. In a sunny day, the temperature of the water wall could be lowered by 2° C. or 3°

C. from the average temperature of the water wall, for example, 20° C. See the thermodynamic calculations below. The cooled water wall provides extraordinary comfort to the room. After sunset, the temperature of the water wall gradually rises. Because of the large thermal mass of the water wall, if the room is properly insulated, comfortable temperature could be maintained throughout the night. In the day time of winter, sunlight enters directly through the window **104** to heat up the water wall, where the insulating shutters **116** are opened to expose the black surface of the water wall **105**. With a conventional window, for example, two windows of 3 ft wide and 4.5 ft high, more than 1 kW of heating power can be obtained. For an entire day, the water wall can be heated up a few degrees from its average temperature, for example 20° C. The warm water wall provides extraordinary comfort to the room. After sunset, the insulating shutters **116** are closed to prevent heat loss through the window. Owing to the large thermal mass of the water wall, comfortable temperature can be maintained continuously throughout the night.

[0019] A typical temperature profile in the summer is shown in FIG. **5**. Curve **501** shows the variation of solar power on the solar photovoltaic panel with time. Curve **502** represents the variation of external temperature with time. As shown, it has 3-6 hours of delay from the variation of the solar power. In late afternoon, between 3 pm and 6 pm, the external temperature reaches maximum. The temperature of the structured water wall **503** shows a similar behavior. Between 3 pm and 6 pm, the temperature of the structured water wall reaches minimum. And it increases slowly after sunset.

[0020] A typical temperature profile in the winter is shown in FIG. **6**. Curve **601** shows the variation of solar power on the window. Curve **602** represents the variation of external temperature with time with a time lag of 3-6 hours. The behavior of the temperature of the structured water wall **603** is similar. Between 3 pm and 6 pm, the temperature of the structured water wall reaches maximum. And it decreases slowly after sunset.

[0021] Following is a thermodynamic calculation for estimating the proper sizes of the elements to achieve maximum comfort.

[0022] First, a moderately sized structured water wall can provide extraordinary comfort for a typical room of 12 ft wide and 16 ft long and 8 ft high in a residential building. Suppose that two sides of the room have walls towards the exterior of the house. In SI units, the area of the walls is approximately 20 m^2 and the area of the windows is 4 m^2. For modern houses, the typical U-value of the insulated walls is 0.3 W/° C.m^2 (Watts per degree Celsius per square meter), and the typical U value of the window is 1.4 W/° C.m^2. The total rate of heat loss is 11.6 W/° C. Suppose that the average external temperature is 30° C., and the average temperature of the water wall is 20° C., the temperature difference is 10° C., and the rate of heat loss is 116 W. Each hour, the heat loss is 417,000 Joule, or about 500 BTU.

[0023] On the other hand, suppose the size of the water wall is 5 ft high 7 ft wide and 6 inch thick. The volume of water is about 0.5 cubic meters. The heat capacity of the water is 4.19×500,000=2,100,000 Joule/° C. Each hour, the temperature drop is 0.2° C. For 10 hours, the temperature drop is 2° C. Therefore, one half metric ton (or approximately one half English ton) of water is enough to keep the temperature of an average-sized, well-insulated room comfortably constant. It is important to note that a 0.5 metric ton water wall, comparable with the weight of a grand piano, is not ax extraordinary burden for an average house. Especially, the water wall is located near the wall, not near the center.

[0024] Next, we estimate how much solar power is required to cool the water wall down by at least 2° C. during the day time. We assume that the external temperature is 10° C. higher than the temperature of the water wall. Using a refrigerating unit with a coefficient of performance (COP) of 6 (see for example W. P. Jones 1994), to bring the temperature of the water wall with heat capacity of 2,100,000 Joule/° C. down by 1° C., an input energy of 2,100,000×10/6=3,500,000 Joule is required to operate the compressor. If the process takes 8 hours, the average power required is 3,500,000/(8×3600) =121 W. To cool down the water wall by 2° C., 242 W of average power is required. Therefore, a 500 W peak power is sufficient. The size of a typical 200 W solar photovoltaic panel is 1 m×2 m. Two 200 W solar photovoltaic panels is of a perfect size to function as an awning for a pair of 3-ft times 4.5-ft windows.

[0025] Finally, we estimate the solar power required to heat up the water wall during the winter. The solar constant is roughly 1 kW per m^2. The area of two standard windows (3 ft times 4.5 ft) is 2.5 m^2. Suppose that the transmissibility of atmosphere and the glass is 60% and the absorbance of the (black) water wall is 80%, the solar power received by the structured water wall is about 1 kW. If the average solar exposure is 6 hours with a sinusoidal profile, the heat absorbed is 10,800,000 Joule, which can heat up the water wall by about 5° C. However, at the same time, there is heat loss though the walls and the windows. The net rise of the temperature of the water wall is about 2-3° C. During the night, the temperature of the structured water wall gradually decreases by about 2-3° C.

[0026] The maximum cooling power and heating power by design is preferred to be greater than for maintaining a comfortable temperature. To avoid excess cooling or excess heating, the operation is regulated by a thermostat. In case of cooling, when the temperature of the structured water wall is lower than a predetermined value, for example, 17° C. or 63° F., the refrigeration unit is turned off. In case of heating, when the temperature of the structured water wall is higher than a predetermined value, for example, 23° C. or 75° F., the insulating shutters are closed. In a cool and cloudy winter day, if the temperature of the structured water wall is too low, an external heater can be tuned on.

I claim:

1. A solar-energized cooling-and-heating system for a room in a building comprising:

- a solar photovoltaic panel installed as an awning above a south-facing window for generating electric power in the summer;
- a DC motor directly driven by the electricity generated by the solar photovoltaic panel;
- a vapor-compression refrigeration unit driven by the DC motor;
- a structured water wall placed in the room near a south-facing window cooled by a heat-exchange coil from the refrigeration unit in the summer and heated by direct sunlight through the window in the winter.

2. The system of claim **1** wherein the cooling coil of a refrigeration unit is placed near the top of the structured water wall.

3. The system of claim **1** wherein the structured water wall comprises a plural of component water containers connected by flanges and pumps.

4. The system of claim **1** wherein each component water container is made of two identical parts preferably made of fiber-reinforced plastics.

5. The system of claim **1** wherein the side of the structured water wall facing the window is colored black to maximize the absorption of sunlight for effective heating in the winter.

6. The system of claim **1** wherein the window side of the structured water wall is covered by a shutter system made of insulating material to allow maximum sunlight to come in the day time and to prevent heat loss in the night.

7. The system of claim **1** wherein the heat generated by the compressed refrigerant is dissipated to the environment air.

8. The system of claim **1** wherein the heat generated by the compressed refrigerant is dissipated to a geothermal heat trap.

9. The system of claim **1** wherein the electrical current from the solar panel is controlled by a switch which is turned off when the temperature of the structured water wall is lower than a predetermined value, for example, 17° C. or 63° F.

10. The system of claim **1** wherein the insulating shutter is controlled by a mechanism which is closed when the temperature of the structured water wall is higher than a predetermined value, for example, 23° C. or 75° F.

11. The system of claim **1** wherein a heating element is installed through a flange near the bottom of the structured water wall, to heat up the water wall with external electrical power in cold and cloudy winter time.

12. The system of claim **1** wherein the structured water wall is placed at any place in the room, and the solar photovoltaic panel is placed in any external location to generate electricity, such that the system is for solar-powered cooling only.

* * * * *