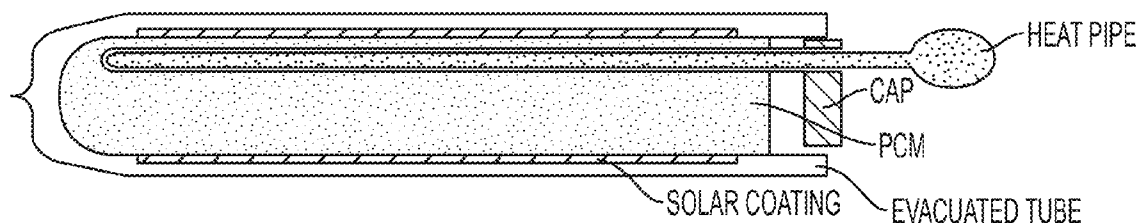




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(19) **United States**(12) **Patent Application Publication**
Zakhidov et al.(10) **Pub. No.: US 2015/0040888 A1**(43) **Pub. Date: Feb. 12, 2015**(54) **INTEGRATION OF PHASE CHANGE
MATERIALS INSIDE EVACUATED TUBE
SOLAR COLLECTOR FOR STORAGE AND
TRANSFER OF THERMAL ENERGY****Publication Classification**(51) **Int. Cl.**
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McKinney, TX (US)(21) Appl. No.: **14/455,766**(22) Filed: **Aug. 8, 2014****Related U.S. Application Data**(60) Provisional application No. 61/863,797, filed on Aug.
8, 2013.(57) **ABSTRACT**

An objective of the invention is to design and develop an effective method to collect and store heat in a solar collector for delayed release. An embodiment of the invention is directed to an evacuated tube collector, where PCM is placed directly inside the void space of the collector tube, next to the heat pipe. The heat pipe is located with phase change material (PCM) in such a way that its thermal connection with the heat pipe can be switched "ON" to start heat transfer from PCM or "OFF" to keep latent heat stored in PCM for delayed usage. In additional, flow of heat exchange fluid through the manifold can enable release of stored heat of PCM to storage tank. Delayed release of accumulated heat in PCM enables added functionality of on-demand operation of SWH.



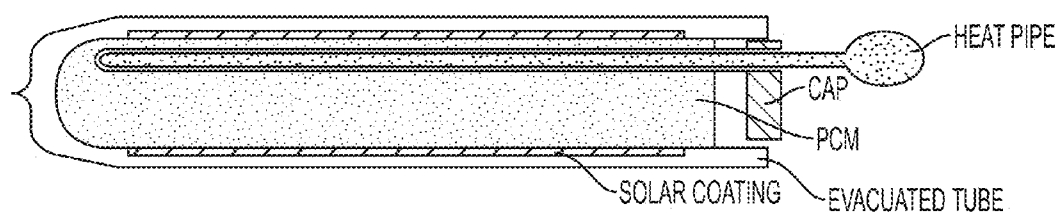


FIG. 1

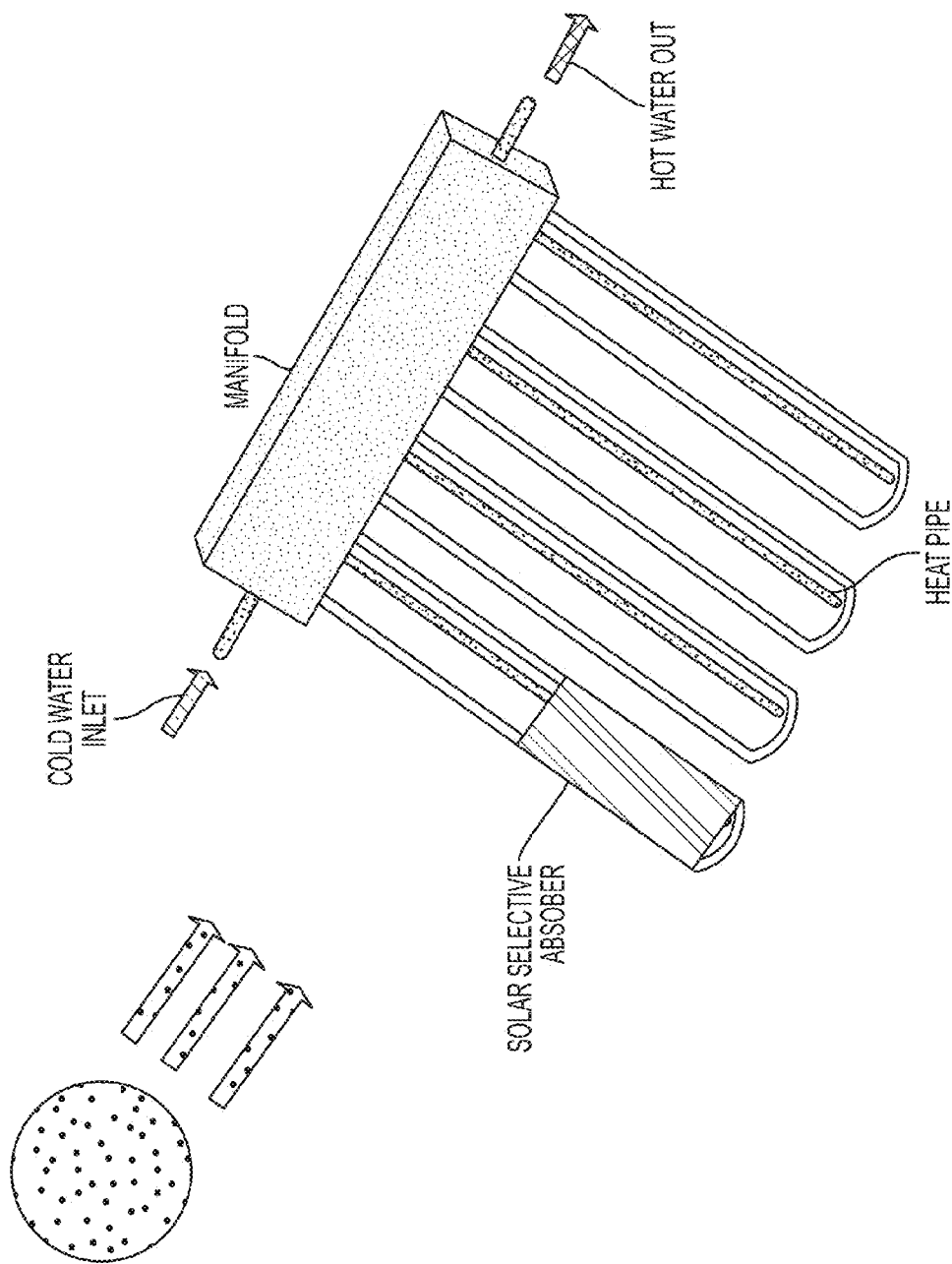


FIG. 2

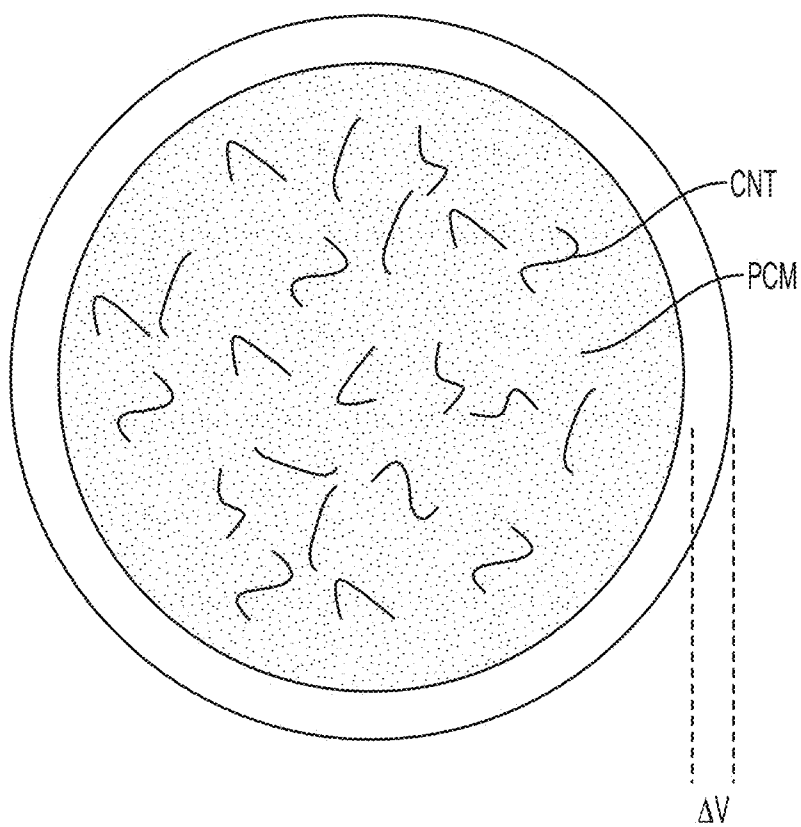


FIG. 3

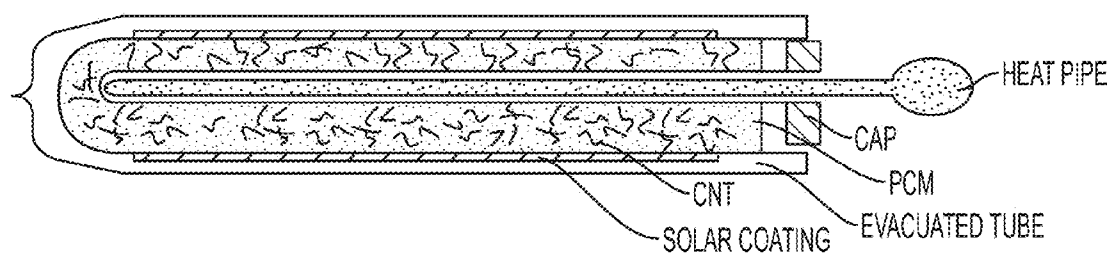


FIG. 4

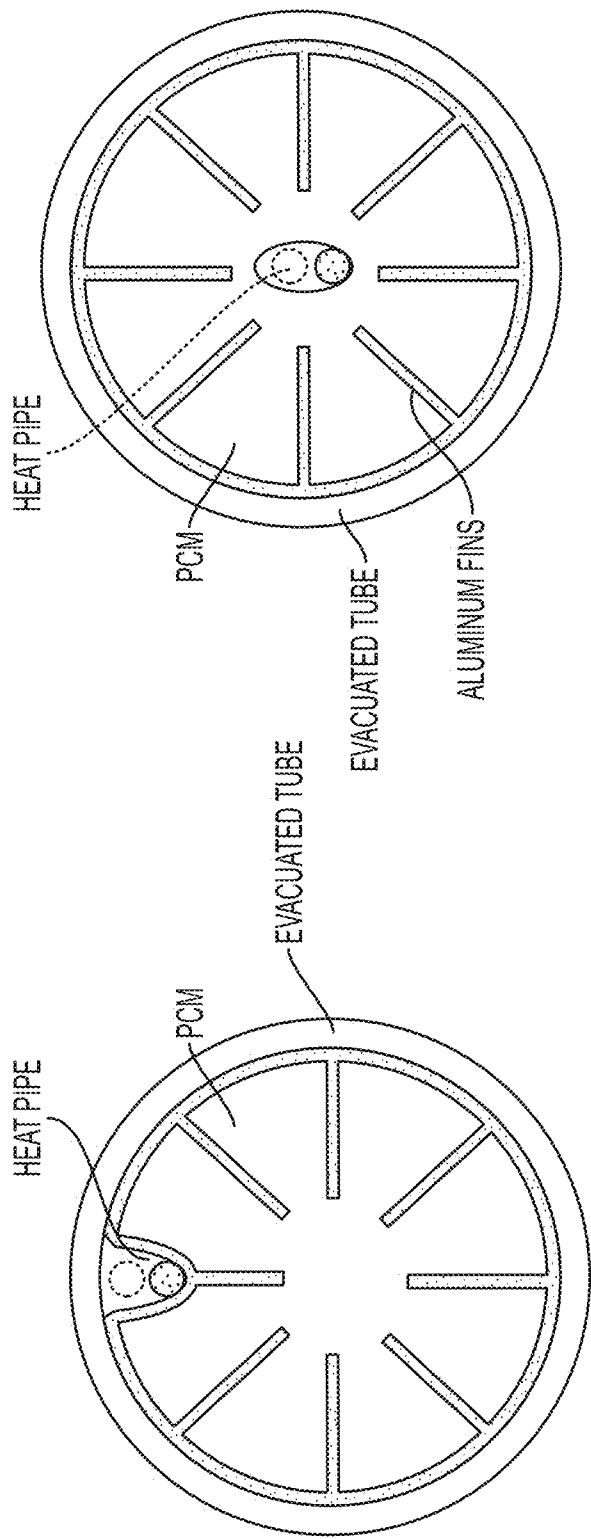


FIG. 5

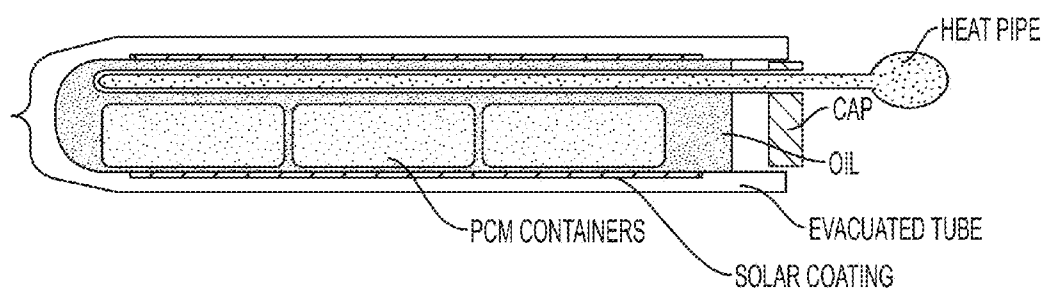


FIG. 6

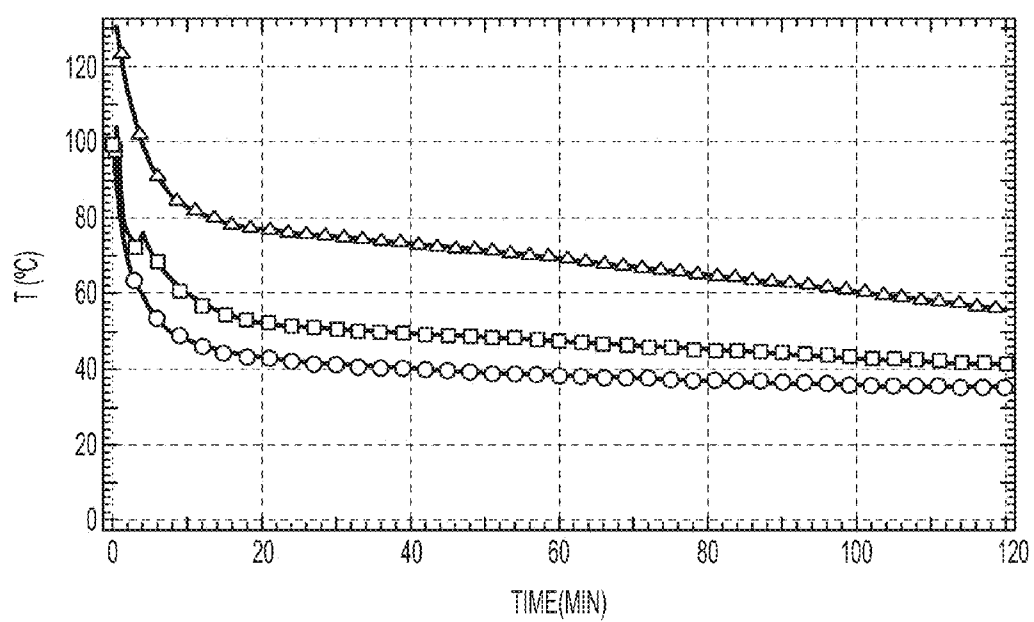


FIG. 7

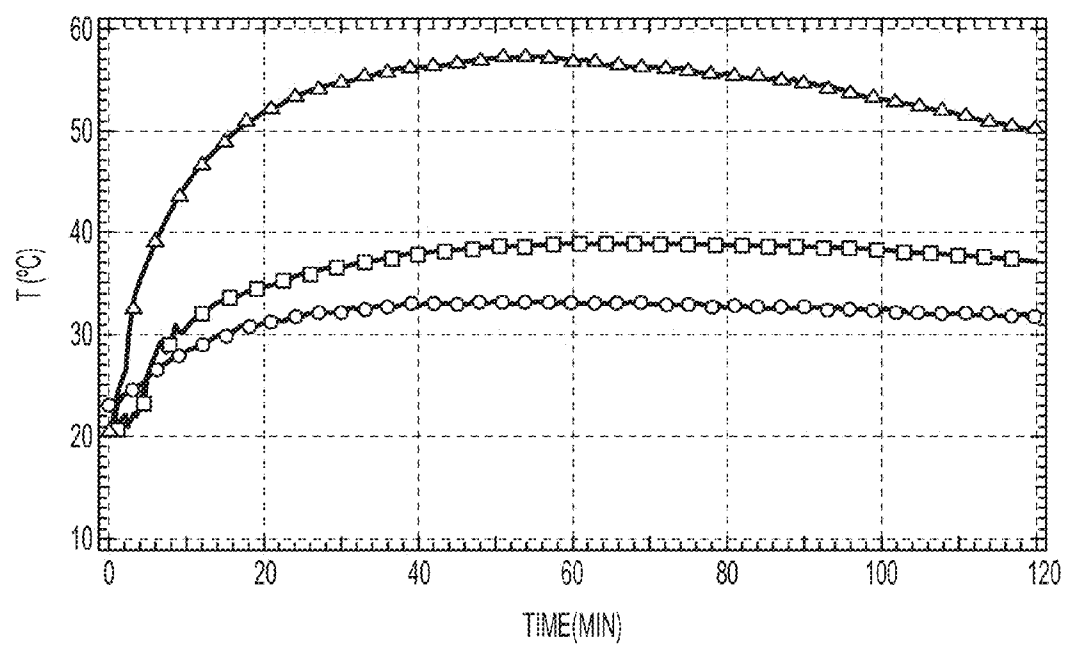


FIG. 8

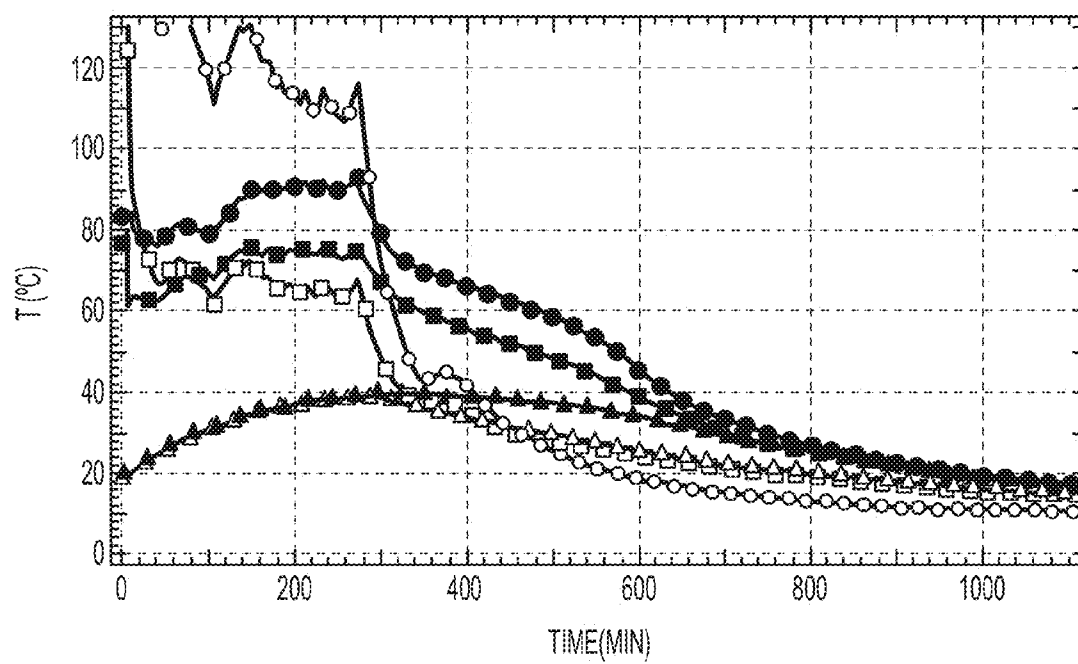


FIG. 9

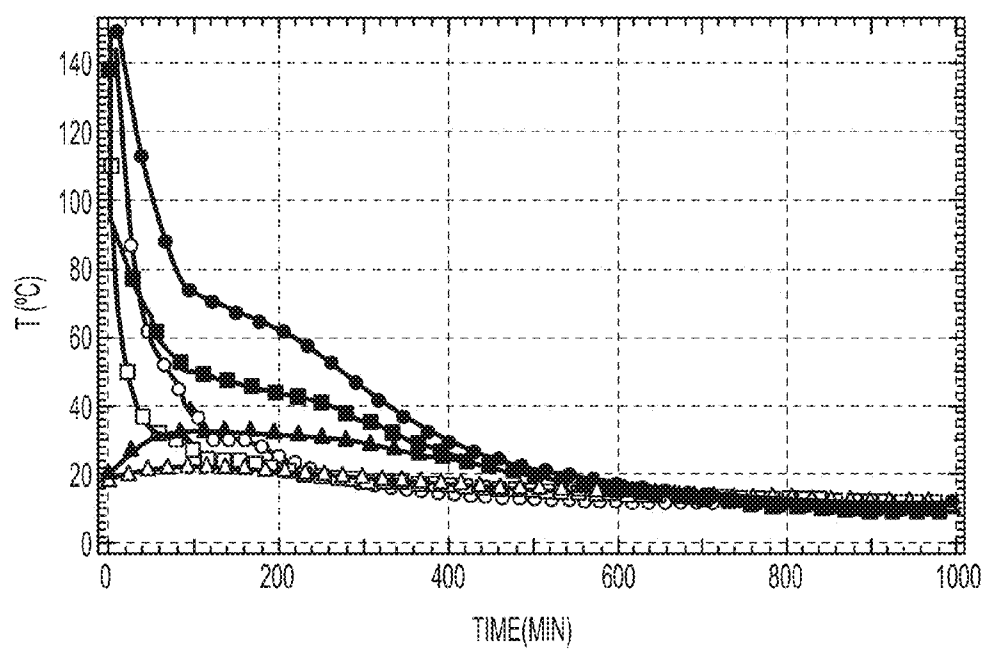


FIG. 10

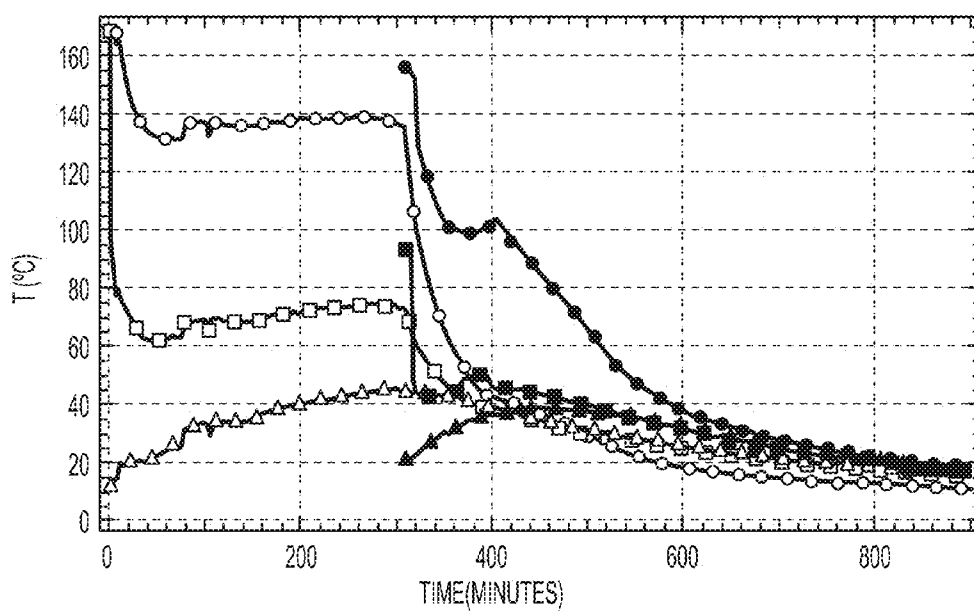


FIG. 11

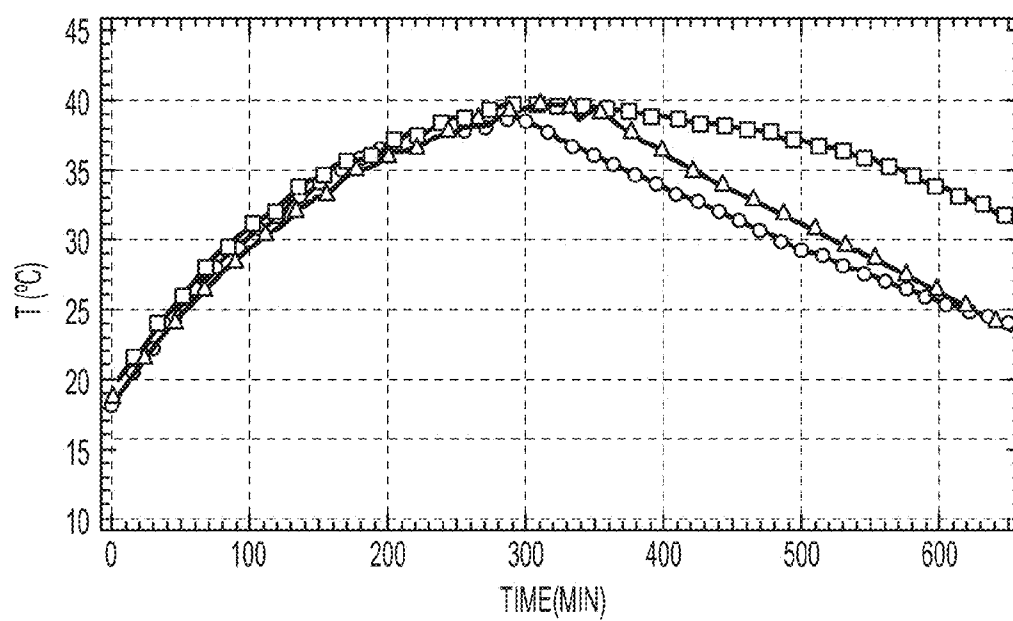


FIG. 12

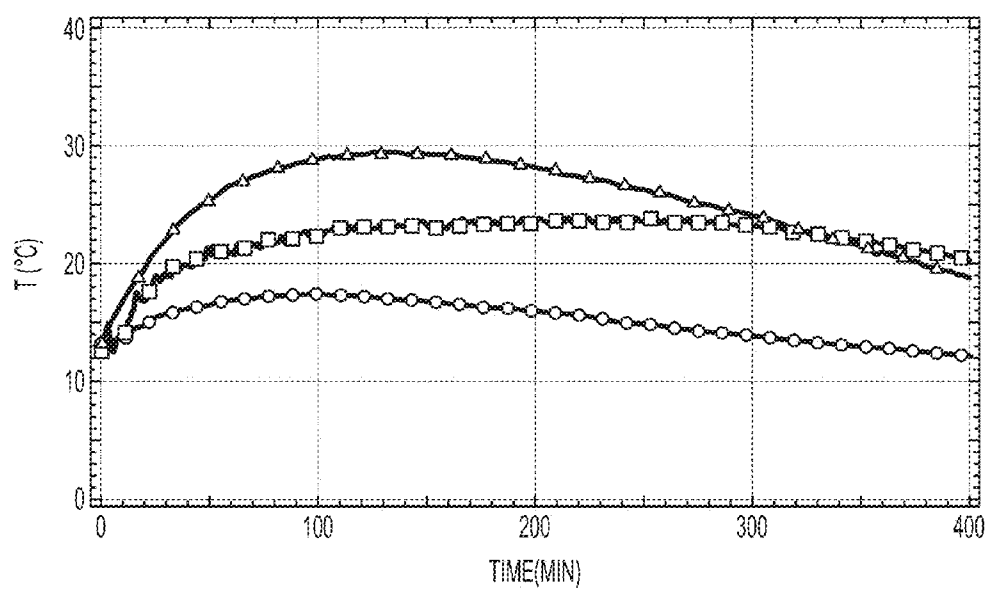


FIG. 13

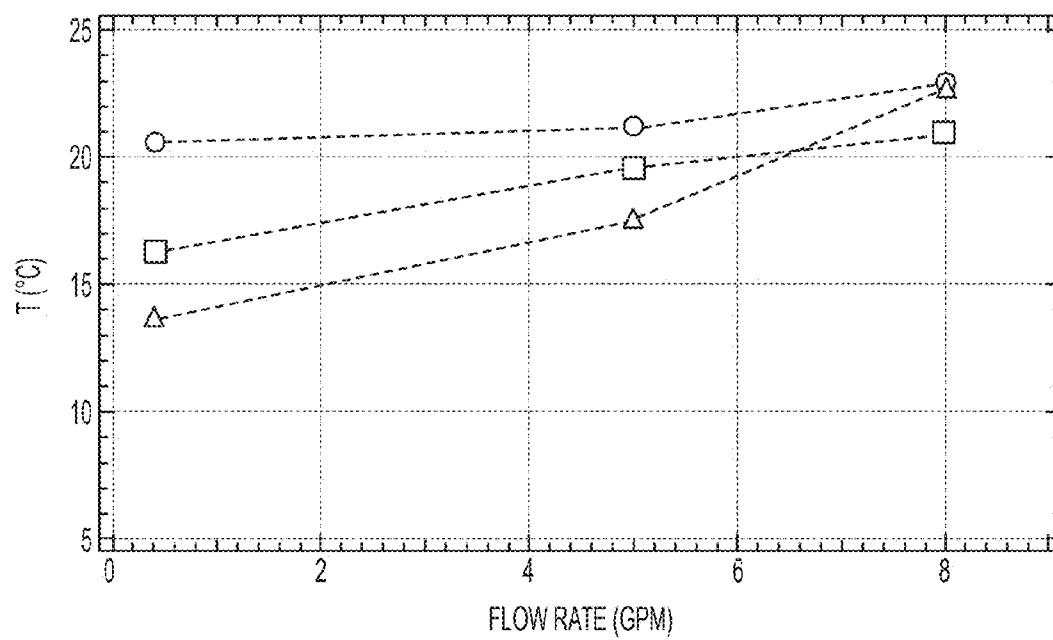


FIG. 14

INTEGRATION OF PHASE CHANGE MATERIALS INSIDE EVACUATED TUBE SOLAR COLLECTOR FOR STORAGE AND TRANSFER OF THERMAL ENERGY

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 61/863,797 filed Aug. 8, 2013, which is incorporated herein by reference in its entirety as if fully set forth herein.

STATEMENT REGARDING FEDERALLY-SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under DOE Phase I STTR Grant No. 87938T12-I awarded by the Department of Energy. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] This invention relates to solar heating of water for industrial and residential applications, and more specifically it relates to evacuated tube collector (ETC) solar water heaters, which use the heat pipe for effective and high temperature water heating and describes a new method to integrate phase change material (PCM) inside the inner space of ETC, in order to store heat and transfer effectively and use it with delay at needed time through heat pipe in contact with the PCM.

[0005] 2. Description of the Related Art

[0006] There are two components required for a functional solar heater: the collector and the storage unit. The collectors are usually in the form of a flat plate or an evacuated tube solar collector (ETSC or shorter ETC). The storage unit is required because at certain times only a very small amount of solar radiation or no radiation will be received. Developing efficient solar energy storage and accumulation devices is an ongoing research by many scientists.

[0007] Among the available techniques suitable for storing thermal energy and for controlling temperature of systems subjected to periodic heating, the use of solid-liquid phase change materials has attracted considerable attention. Phase change materials (PCM) can store 5-14 times more heat per unit volume than sensible storage materials while the absorption and the release of that heat happen at a nearly constant temperature. Therefore, PCMs are suitable for energy storage and temperature control systems.

[0008] When a temperature peak occurs and temperature reaches a certain value known as melting point T_m , PCM melts and absorbs the excessive energy (known as latent heat) by undergoing a phase transition and releasing the absorbed energy later or when the demand peak has passed. Before a solid can melt, it must absorb sufficient energy to overcome the binding forces which maintain the solid structure. This energy for complete melting is referred to as the latent heat of the material and represents the difference in thermal energy levels between liquid and solid states. Conversely, solidification of a liquid requires the removal of this latent heat with the consequent structuring of atoms into a more stable lattice.

[0009] There are a large variety of PCMs that melt and solidify at a wide range of temperatures, making them attrac-

tive in a number of applications. Examples of phase change materials include water, salt hydrates, certain hydrocarbons, metal alloys and paraffin. They have large spectrum of latent heats and melting temperatures. Therefore, the PCM melting and solidifying temperature range can be easily matched with the system's operating temperature for the phase-change process to be effective. Other advantages of these PCMs include: physical properties, chemical properties (no toxicity and no fire hazard), and low cost and availability.

[0010] There have been many investigations on the utilization of PCMs inside storage tanks in solar applications. One of the challenges in the application of phase change materials is increasing their thermal conductivity while maintaining their high latent capacity. Recently, the combination of carbon nanotube arrays and PCM has been demonstrated to be very attractive for enhancing the thermal conductivity of the PCMs. Carbon nanotubes (CNTs) with extremely high thermal conductivity have shown tremendous potential for heat transfer applications. Compared with the other heat transfer promoters, CNTs yield better stability in an organic matrix. Several researches have been reported wherein CNTs are embedded in the base fluids and phase change materials to increase their thermal conductivities.

[0011] Although PCMs are good candidates for storage applications, not all PCMs are ideal for our novel idea. The PCM to be used in the evacuated tube solar collectors should have a high melting temperature, between 100° C. and 180° C. PCMs with high melting temperature usually have low thermal conductivity, high cost, subcooling, and poor stability during the temperature cycling; the number of suitable phase change materials which are suggested in the literature is very limited. TABLE 1 gives several suitable PCMs for our applications. All of these materials are safe, non-expensive and nontoxic with high melting temperature and latent heat.

[0012] The claimed invention relates to a system that combines the collection and the storage of thermal energy both in a single unit, and namely inside the evacuated tube of solar collector. Previously PCM has only been used inside flat panel collectors, and to our knowledge there has been no integration of PCM inside evacuated tube. The integrated collector is, in general, simpler than conventional domestic water heating system with PCM inside storage tank and has many advantages, including weight and cost savings.

TABLE 1

Substance	Melting Temp. (° C.)	Latent Heat (J/g)
Erythritol	119	332-340
Hexacosane Paraffin	56	257
Tritriacontane Paraffin	74	268
Pentaerythritol	186-187	287-298
Azelais acid	98-108	174
Sebacic acid	130-134	228
Dimethyl Terephthalate	142	170
P-Toluic acid	180	167
Octadecanamide	106	211
Urea	133-135	170-258
HDPE	110-150	140-200

[0013] Among the above PCMs, paraffin and erythritol have been chosen as preferred embodiments that are safe, non-toxic, non-expensive and readily available. The thermal properties of paraffin and erythritol make them excellent phase change materials.

SUMMARY OF THE INVENTION

[0014] An objective of the invention is to design and develop an effective method to store heat inside of an evacuated tube solar collector (ETC) for delayed release. An embodiment of the invention is directed to a previously developed evacuated tube collector, which comprises of two concentric glass tubes: the first inner glass tube is sealed on one end and fused to the second outer glass tube on the other end via a flared edge, the second tube is sealed at the free end, vacuum is created between the first tube and the second tube, the outside of the inner tube is coated with highly light selective "black" layer, and a heat pipe supported by a metallic fin is inserted inside the inner tube space, connecting it to the heat exchanger manifold. The claimed invention involves filling the void space of the first inner tube, where the heat pipe is located with phase change material in such a way that it is thermally connected with the heat pipe via fins or other media. Moreover connection of PCM to heat pipe can be switched either "ON" to release the latent heat stored in PCM into heat pipe and thus into manifold or "OFF" to keep heat accumulated and stored for later transfer. Alternatively, release and storage of the energy in PCM may happen by controlling the flow of water through the exchanger manifold. The heat is then accumulated effectively from solar radiation in a "stagnated mode", when water flow is OFF, and released later, after sunset by switching the water flow ON. In case of a closed loop system an anti-freeze fluid may be used instead of water as heat transfer fluid.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 is a through, side view of an evacuated solar tube collector with incorporated phase change material;

[0016] FIG. 2 illustrates an evacuated tube solar collector assembly;

[0017] FIG. 3 is a schematic, top view of the evacuated tube collector with carbon nanotube percolated phase change material for high thermal conductivity. Due to volume change ΔV upon phase transition, the cavity would not be completely filled with the phase change material;

[0018] FIG. 4 is a through, side view of an evacuated solar tube collector with incorporated phase change material percolated with carbon nanotubes;

[0019] FIG. 5 is a schematic, top view of the evacuated tube collector demonstrating the function of the switchable heat pipe and phase change material, two different fin designs are shown;

[0020] FIG. 6 is a through, side view of an evacuated solar tube collector with incorporated phase change material enclosed in containers. Oil is used to fill the volume between the inner glass tube and PCM containers;

[0021] FIG. 7 is a plot of fin temperature inside the evacuated tube solar collector in the case of (○) a tube filled with paraffin (56° C.), (□) a tube filled with paraffin (73° C.), and (Δ) a tube filled with erythritol (119° C.);

[0022] FIG. 8 is a plot of water temperature inside the small storage tank in the case of (○) a tube filled with paraffin (56° C.), a (□) tube filled with paraffin (73° C.), and (Δ) a tube filled with erythritol (119° C.);

[0023] FIG. 9 is a plot comparing a typical solar collector with evacuated tubes and a paraffin filled solar collector in normal operation, (○) temperature inside a typical evacuated tube, (●) temperature inside a paraffin filled evacuated tube, (□) manifold temperature of typical solar collector, (■)

manifold temperature of paraffin filled solar collector (Δ) water temperature of typical solar collector (▲) water temperature of paraffin filled solar collector;

[0024] FIG. 10 is a plot comparing a typical solar collector with evacuated tubes and a high temperature paraffin PCM filled solar collector in stagnation and cool down operation, (○) temperature inside a typical evacuated tube, (●) temperature inside a paraffin PCM filled evacuated tube, (□) manifold temperature of typical solar collector, (■) manifold temperature of paraffin filled solar collector, (Δ) water temperature of typical solar collector, (▲) water temperature of paraffin PCM filled solar collector;

[0025] FIG. 11 is a plot comparing a typical solar collector with evacuated tubes in normal operation and an erythritol filled solar collector in stagnation and cool down operation. (○) temperature inside a typical evacuated tube, (●) temperature inside a paraffin filled evacuated tube, (□) manifold temperature of typical solar collector, (■) manifold temperature of paraffin filled solar collector, (Δ) water temperature of typical solar collector, (▲) water temperature of erythritol filled solar collector;

[0026] FIG. 12 is a plot of water temperature of storage tank during normal operation in the case of a 10 tube solar collector array: (○) with empty tubes, (□) with tubes filled with paraffin (73° C.), and (Δ) with combination of tubes filled with paraffin (73° C.) and tubes with erythritol (119° C.);

[0027] FIG. 13 is a plot of water temperature of storage tank after system stagnated in the case of a 10 tube solar collector: (○) with empty tubes, (□) with tubes filled with paraffin (73° C.), and (Δ) with combination of tubes filled with paraffin (73° C.) and tubes with erythritol (119° C.); and

[0028] FIG. 14 is a plot of water temperature increase in storage tank in case of different flow rates through the manifold of solar collector. The temperature increase ΔT of a typical system (○) in normal operation, a system (□) with tubes filled with paraffin (73° C.) in normal operation, a system (Δ) with tubes filled with paraffin (73° C.) operating with energy only stored in phase change material inside the evacuated tube collector.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0029] Solar water heater (SWH) is a cost-effective way to generate hot water for commercial or residential applications. Solar water heating systems include storage tanks and solar collectors. Two types of solar collectors most frequently used are: flat plate collectors and evacuated tube collectors. FIG. 1 shows a schematic of an evacuated tube collector (ETC). Two glass tubes are sealed at the top and bottom. High vacuum is created between them to provide excellent thermal insulation. The inner tube is coated with a highly absorbing layer. Once the tube is exposed to the sun, the heat is mostly transferred to the heat pipe inside the inner tube. The evacuated space between the two tubes does not allow the heat to escape to the environment. The heat pipe is supported by metal fins inside the inner tube. The heat pipe is also evacuated and contains a small amount of heat transfer fluid (typically water) that transfers the heat to the system manifold on the top. The heat pipe is made of copper. FIG. 2 illustrates an ETC assembly. The system consists of an array of evacuated tubes and a manifold that connects to each evacuated tube's heat pipe. The heat transfer fluid flows through the manifold that is warmed up by the heat generated in the evacuated tubes and transferred by the heat pipe. In commercially available SWH

systems utilizing ETC collectors, the available space around the heat pipe and metal fins in the interior of the collector is left void. In the present invention we suggest to use PCM right in the void space of the inner tube of the evacuated tube. The phase change material has good thermal contact with the solar selective coating through the inner walls, with the metallic fin insert along the walls, and with the heat pipe. In addition, the phase change material is subjected to low thermal losses, because the inner walls are separated by a vacuum gap from the environment. To further improve the thermal conductivity of the phase change material and the efficiency of the cooling and melting process, carbon nanotubes or other carbon nanomaterials are added to the phase change material, as seen in FIGS. 3 and 4. The suggested addition of phase change materials improves significantly the performance of the solar water at delayed operation of heating tube.

[0030] Experiments and simple calculations have show that the stored energy inside the tube can reach about 100 to 600 kJ/kg. This energy is enough to keep heat pipe generating energy transferred to the manifold with the outer water circuit for about 2-3 hours depending on the type of heat pipe and the type of PCM. If the heat pipe is not inserted in the evacuated tube then the energy stored in the PCM can be stored for many hours and experiments show that it can be stored without significant change in temperature for 10 hours. This means that the system can be switched ON anytime for operation depending on the demand. The heat pipe can start operating when the customer needs hot water. That operation requires a special switch, which starts the operation of a heat pipe, directly from PCM inside the inner tube. The system is turned ON by mechanically placing the heat pipe in contact with heat transfer fins inside the tube, as shown in FIG. 5. The system is turned OFF and set to operate in heat storage mode by detaching the heat pipe. In addition, the solar water heater is turned OFF when the water, or anti-freeze fluid, flow is stopped. In this case all energy is accumulated into the PCM. Finally, the system is turned ON by allowing water to flow through the manifold and resuming heat transfer from solar collector assembly to the storage tank.

[0031] The phase transition of PCM between solid and liquid causes significant change in the volume ΔV of the material. The volume change can cause damage to glass ETC tubes. Cracking of the glass tubes can be avoided by partially filling the void inside the ETC tube. The PCM volume will change and return to original volume at room temperature. FIG. 3 shows a schematic of ETC tube partially filled with PCM to accommodate expansion during increase to temperature. Alternatively, protection of ETC tubes is achieved by placing the PCM material inside a container. The containers with PCM can be built with thin stainless steel or aluminum and placed into the ETC. In addition, containers of PCM can be built with foil, metalized films, mylar or other polyester type materials. The containers (small bags) in this case can deform and can be easily inserted into the ETC tube. Although a bigger percentage of volume of ETC tube is filled with small bags as compared to rigid containers, a significant part of ETC remains empty. The remaining part is filled with heat transfer oil (conventional oil, silicone oil or other type) which improves heat transfer but also has high sensible heat storage (FIG. 6).

[0032] In one embodiment, the operation of a solar water heater system is improved by the addition of metallic reflector (e.g., corrugated galvanized steel panel) behind the ETCs. The additional reflector increases the incident insolation on

the collector array and provides heating along most of the entire diameter, as compared to only the top half of collector array being insulated without the back reflector. With more uniform radial heating of the collector, the heat pipe operates more efficiency when placed in the middle of the collector, as shown in FIG. 5. In such central configuration, heat fins are to be placed radially in order to provide good thermal contact between the solar selective coating and the heat pipe.

Example 1

Performance of Evacuated Tube Collector Systems Filled with Phase Change Materials

[0033] In order to evaluate the performance of phase change material inside evacuated tube collector, field test on 0.5 meter collectors were carried out. FIG. 7 shows curves of the temperature inside the tube in three different cases. Two paraffin based PCM materials with different working temperatures (56°C . and 73°C .) were added inside the tube collector are compared to a standard tube collector. Also, erythritol was used for comparison with paraffin PCM. The temperature of metal fins of ETC was measured after exposure to sun for 3 hours and during the cool down in the shade. A small water tank (600 ml) was placed on top of heat pipe. In the case of the 56°C . PCM filled tube; we observe a significantly faster cooling rate. In the case of paraffin 73°C . the temperature inside the tube remains higher than paraffin 56°C . In FIG. 8 we show the recorded temperatures inside small water tank on the top of heat pipe. The heat pipe effectively transfers energy stored inside the PCM to the water tank. We observe that the energy from paraffin 56°C . filled tube (○) increase the water temperature by 11°C . Paraffin 73°C . (□) and erythritol (A) caused temperature increase of 19°C . and 35°C . respectively. We observe that higher temperature increase in the case of erythritol because the interior temperature of tube remains at higher temperature for longer time and therefore the heat pipe operates more efficiently and for extended time. The stored energy can be used by the SWH to provide warm water after sunset. On the contrary, the standard tube may warm up faster, but at the same time its temperature falls below heat pipe operational temperature faster in the dark due to lack of heat storage capability.

[0034] The operation of two evacuated solar tube solar collector systems with and without PCM filled tubes were also compared. Each solar system had 10 evacuated tube collectors attached a heat exchange manifold and a pump circulated 40 liters of water through the systems. A flow rate of 0.2 GPM was maintained during the warm up and cool down of the system. For each system we recorded the temperature of the water in the tanks, the temperature of the manifold and temperature inside the ETC. In normal operation the systems were operated with constant water flow between the collector and tank. Both solar collectors were allowed to operate under the sun for several hours. The systems were then covered at the same time and water kept flowing with constant rate. Temperatures recorded during warm and cool down of system and are shown in FIG. 9. The temperatures inside the evacuated tube of solar collectors correspond to (○) and (●) for typical ETC and PCM filled ETC. In normal operation the temperature increases as sun rises in the morning. The value will eventually reach a maximum value and stabilize. The value inside the tube depends on the flow rate of the water, solar intensity, the presence and type of PCM material. A typical tube will warm up to 120°C .

as shown in (○) points in FIG. 9. The high temperature paraffin we used has a melting point of 73° C. The paraffin filled tubes temperature was about 90° C., solid circle points (●), above the melting point. After approximately 6 hours both systems were covered and cool down temperatures was reported. The manifold and water tank of typical solar collector begins cooling down rapidly (solid squares points (□) and empty triangle points (Δ) in FIG. 9). In the case of paraffin filled collector the cool down of manifold (■) and water tank (▲) is much slower. It is important to note that we used not insulated tanks for water storage and heat losses during the experiment were continuous.

Example 2

On-Demand Operation of Evacuated Tube Collector SWH System Filled with Phase Change Material

[0035] In FIG. 10 we report results recorded during cool down of systems. Initially, both solar collectors were kept in stagnation mode, i.e. without a water flow through heat exchanger. A few seconds before systems being covered from sunlight, water flow started with the rate of at 0.2 GPM.

[0036] We observe the temperature inside evacuated tubes to be significantly higher compared to operation in normal mode, since no heat transfer to water is possible. We can assume that phase change of paraffin has occurred for the majority of the material since the temperature inside the tubes with paraffin has exceeded 73° C. We observe the fast cool down of standard evacuated tube (○) and the delayed cool down of PCM tubes (●). While systems are stagnated, the majority of absorbed energy is accumulated in PCM materials. Once the water flow is started, the energy can be transferred to water through the heat pipe and the manifold assembly. Therefore, the PCM filled tubes enable operation of the system in the dark. The paraffin filled ETC tube cool down curve shows a plateau around 73-75 C during cool down. The heat exchanger manifold of typical solar collector begins cooling down rapidly (□) in FIG. 10. In the case of paraffin filled collector the cool down of manifold (■) is slower due to heat provided by PCM material. The effect of PCM to solar water heater operation is even more pronounced when comparing the temperatures recorded in the two water tanks (▲ and Δ of FIG. 10). The temperature of typical collector water tank remains unaffected when collector is not exposed to sunlight (Δ). In contrast, the PCM collector tank is warming up at the same time (▲). The circulated water through the manifold of collector and tank was 40 lt. The recorded increase of temperature in uninsulated tank was 12° C. A Latent Heat (heat of fusion) of paraffin is 210 KJ/kg, materials with higher heat of fusion have the potential to provide improved delayed cooling or on-demand operation of solar water heaters after dark or in cloudy weather.

[0037] Erythritol has higher of heat of fusion (known also as latent heat) of 340 KJ/kg and also increased melting point. The phase transition point is 123° C. We compared the operation of a solar collector filled partially with erythritol and a typical solar collector with empty ETC. The PCM filled collector was consisted of 10 filled tubes with erythritol inside mylar baggies and heat transfer oil. In FIG. 11, we show the operation of the typical system during normal operation under sunlight. The temperature inside the evacuated tube reaches 140° C. during normal operation (○), while heat exchanger manifold temperature is about 70 ° C. under full spring sun (□). Once the system is covered (i.e. ETC collector

is shaded from sunlight), both the temperatures rapidly decrease and also water temperature begins to decrease. The erythritol filled solar collector was operated in stagnation during the day (meaning that water was not running through the exchanger). The temperature inside the tubes reached 158° C. (●), (since the heat was not extracted by water flow) and the PCM was melted at this high temperature, far above melting temperature of erythritol. The temperature inside erythritol filled ETC starts decreasing after system is shaded and water once a flows begins. A plateau is visible around 100° C. due to latent heat release of erythritol (●). The temperature continues to slowly cool down for several hours enabling continuous operation of heat pipe and system. The water temperature of erythritol system tank (▲) increases at higher rate compared to normal operation. Therefore, it is possible to have a SWH that can accumulate energy for use in the nighttime, without the use of insulated water tank.

Example 3

Operation of ETC Solar Collector Assemblies with PCM

[0038] Two systems (typical ETC system and PCM integrated system) were operated daily under similar conditions. The solar water heaters were operated in two different modes, first in normal operation the water is circulated between the manifold of the collector at a constant flow rate and the water tank. Second, in stagnation mode, no water flow was initiated through the manifold for an extended time and the pump was not started until PCM in both systems was melted and collectors have been covered completely from sun. The temperatures of water in the storage tank of a typical solar water system and a PCM integrated systems are shown in FIG. 12 for normal operational mode. In all cases the temperature appears peak at time the systems are covered, where the temperature in tank of system without PCM cools down rapidly. In contrast, the tank of paraffin filled system shows a slower cooling rate and the significant heat loss from uninsulated tank does not allow the water temperature to rise perceptibly. The paraffin/erythritol system also shows the delayed cooling effect of water temperature. Also, we notice that it decreases at a faster rate due to operation below Erythritol's melting point.

[0039] The storage tank temperature of the three systems is shown in FIG. 13 during cool down after systems kept in stagnation. In this case, the two solar collector systems were kept in stagnation mode, i.e. without a water flow through heat exchanger. A few seconds before systems were covered from sunlight, water flow started at the rate of at 0.2 GPM. It was observed that the temperature of the manifold is significantly higher compared to operation in normal mode, since no heat transfer to water is happening. It can be assumed that phase change of PCMs has occurred for the majority of the material since the temperature inside the tubes with paraffin has exceeded the melting point. While systems are stagnated, the majority of absorbed energy is accumulated in the PCM and once the water flow is started, the energy can be transferred to water through the heat pipe and the manifold assembly. The water tank temperature of a standard system increases only by a few degrees after collector is shaded (○), while the water tank temperature of PCM systems increases significantly as heat is released by the PCM. The circulated water through the manifold of collector and tank was 40 L and the recorded increase of temperature in uninsulated tank was

around 12° C. (□), while the system that uses a combination of Erythritol and paraffin showed a temperature increase of 16° C. (Δ). Therefore, the PCM allows the operation of the system on demand.

Example 4

Energy Accumulation and Transfer Calculation Using Erythritol Inside ETC

[0040] Peak solar energy absorption of an evacuated tube collector can be calculated by using the following assumptions: the absorber area of a typical 1.8 meter long collector tube is 2540 cm²; without reflective panels on the underside of the collector, the effective absorber area is reduced by 50%; solar irradiance is 100 mW/cm²; collector solar absorption is 92%. This results in a peak solar power absorption of 117 W per tube, corresponding to 117 W·h of energy every hour under the AM1.5 solar irradiance.

[0041] If the inside tube of the same 1.8 meter long evacuated tube collector was filled with erythritol, which has latent heat of 330 J/g (note that 1 Joule is equal to 1 W·sec) and density of 1.54 g/cm³, that would amount to approximately 3.86 kg of erythritol in the inner volume of 2660 cm³. This translates to stored energy of 1270 kJ. Estimating 66% efficiency of the latent heating with erythritol as compared to solar heating, the stored latent heat would provide the same amount of energy as 2 hours of peak solar power output. That is significant amount of stored heat available even at night.

Example 5

Example of ETC with CNT Coating as Selective Solar Absorber and Filler for Increased Heat Transfer

[0042] ETC array used with reflectors for solar radiation concentration or parabolic trough collectors operate at higher temperature, as compared to the conventional solar water heater systems. Typical cermet solar selective coating of ETCs is limited in application to 400° C. due to the delamination of the selective coating from the substrate. For high temperature applications, such as ETCs with reflectors or parabolic troughs, carbon nanotube sheets can be used as the solar selective coating that are thermally stable above 600° C., which is the limiting temperature for the glass structure of the collectors. With successful implementation of solar selective coating with thermal stability above 600° C. a different type of phase change material must be used for effective operation.

[0043] Molten salts and salt eutectic systems are ideal for high temperature storage applications. Molten salt systems have a wide range of tunable temperatures from 250° C. to 1680° C. with latent heat from 68 to 1041 J/g. Significant disadvantage of these systems is their low thermal conductivity. In order to improve the thermal conductivity of PCM incorporated into a high temperature ETC or parabolic trough, carbon nanotubes are incorporated into the PCM mixture, as shown in FIG. 3. With proper surface modification of carbon nanotubes, via etching or doping, favorable surface energy interaction can be achieved in order to facilitate mixing between PCM and CNTs and ensure long term stability of the mixture. Ultra low density and porous nature of CNTs combined with excellent thermal conductivity properties means that volume fraction of CNTs needed to improve thermal performance of PCM is not significant. A cost saving

alternative to carbon nanotubes, are electrospun nanofibers, which undergo further pyrolysis to produce carbon nanofibers. Such configuration will also increase thermal conductivity of the high temperature PCM and enable energy storage in high temperature solar collectors systems.

Example 6

Flow Rate Effect in Operation on ETC with PCM

[0044] The flow rate of heat transfer fluid through the manifold of SWH system affects the performance of system in normal operation during the day and also during on-demand operation. FIG. 14 is a plot of water temperature increase in storage tank in case of different flow rates of water through the manifold of solar collector. Improved operation of the SWH systems was achieved with addition of a metallic reflector. The temperature increase ΔT of a typical system (○) in normal operation without PCM increase with higher flow rate. The storage tank temperature of system with tubes filled with paraffin (73° C.) in normal operation (□) is also increasing from 16° C. at 0.4 GPM to 21° C. at 8 GPM. On-demand operation of a system with ETCs filled with paraffin (73° C.) operating with energy only stored in phase change material inside ETC is also shown in FIG. 14 (Δ). The effect of flow rate in the system is more pronounced in this configuration. The temperature increase in storage tank is 14° C. at 0.4 GPM, while the increase at 8 GPM is 22° C.

[0045] While particular embodiments of the present disclosure have been illustrated and described, it would be obvious to those skilled in the art that various other changes and modifications can be made without departing from the spirit and scope of the disclosure. It is therefore intended to cover in the appended claims all such changes and modifications that are within the scope of this disclosure.

What is claimed is:

1. A solar collector comprising:
an evacuated tube collector (ETC) or an ETC array;
a phase change material, wherein the phase change material is located within the inner space of the evacuated tube collector; and
a heat pipe, wherein the heat pipe is located within the inner space of the evacuated tube collector and wherein the heat pipe is in thermal contact with the phase change material.
2. The solar collector of claim 1, wherein the phase change material comprises materials having high transition temperatures.
3. The solar collector of claim 1, wherein the phase change material comprises salts.
4. The solar collector of claim 1, wherein the phase change material is selected from the group consisting of erythritol, pentaerythritol, azelaic acid, sebacic acid, dimethyl terephthalate, p-toluic acid, octadecanamide, urea, and high density polyethylene.
5. The solar collector of claim 1, wherein the heat is stored within the phase change material.
6. The solar collector of claim 1, wherein the thermal contact between the heat pipe and the phase change material is controlled by a switching mechanism.
7. The solar collector of claim 1, wherein the heat pipe further comprises a heat transfer fluid.
8. The solar collector of claim 7, wherein the heat transfer fluid is water.

9. The solar collector of claim 1, wherein heat is transferred from the phase change material to the heat pipe.

10. The solar collector of claim 1, wherein heat is transferred from the heat pipe to the heat transfer fluid.

11. A solar collector of claim 1, wherein the heat pipe is in thermal contact with the phase change material, and heat transfer from PCM to water storage tank is controlled by water flow through a heat exchanger manifold.

12. The solar collector of claim 1, wherein the heat transfer from PCM to the water storage tank is controlled on demand.

13. The solar collector of claim 1, wherein carbon based materials are mixed inside the phase change material to improve heat conductivity of system.

14. The solar collector of claim 1, wherein carbon nanotubes are added to the phase change material.

15. The solar collector of claim 1, wherein pyrolyzed electrospun fibers are added to the phase change material.

16. The solar collector of claim 1, wherein the phase change material inside the ETC tubes placed inside multiple containers.

17. The solar collector of claim 16, wherein heat transfer oil is added inside the ETC tubes with phase change materials filled containers.

18. The solar collector of claim 1, wherein the solar collector is used with a solar concentrating arrangement.

19. The solar collector of claim 1, wherein the heat pipe is supported by the heat fin in the middle of the ETC.

20. The solar collector of claim 1, wherein heat fins are placed radially.

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