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Low-Cost Solar Heating Reservoir Manufactured by Double-Coating a Water Tank with Polymeric Materials

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Abstract: One of the main needs of the modern society is the availability of low-cost energy sources, and the solar energy arises as an interesting alternative for both the generation of heat and electricity. In this work, a low-cost solar energy reservoir is proposed for domestic water heating. It is comprised of a thermoplastic (polyethylene) water tank thermally insulated by means of two different polymeric coatings, an acrylonitrile butadiene rubber foam, NBR, and a metalized polyester layer. The solar system also contains a flat collector based on a ceiling panel made of poly(vinyl chloride), PVC, coated with carbon black-filled glaze. The system design is cost-effective because of all the parts involved in the solar heating are made from commodity plastic materials. These plastic components present wide commercial availability and are easily handled, so that they can be rapidly assembled to build the entire system. Therefore, the solar heating system is simple, modular and easy-scalable, and may be even self-manufactured by the final user. It is an affordable option to the traditional high-cost copper, aluminum and glass solar panels and boilers or tanks used for heat storage.

Keywords: solar energy; thermal insulation; heat water reservoir; double-coating; polymeric materials

1. Introduction

Modern societies demand new low-cost energy sources, and solar energy arises as an interesting alternative for the generation of both electricity and heat. Currently, solar energy is used on different aspects of daily life, including house heating, water supply, and cooking [1]. Moreover, solar thermal energy applied to the power generation is dramatically increasing worldwide, with thermal power plants completed and under construction in Europe, USA, Australia, and Africa [2].

Despite the fact that much effort has been made by research agencies, governmental policies, and manufactures to adequate the production of solar thermal collectors to the demand of hot water [3], the conversion, storage and application of solar energy still challenges the development of a sustainable energy system [4]. Two major reasons for this are: solar irradiance, consumption and thermal accumulation are inherently transient and intermittent over space and time [3,4]; and the visible light (~44 % of the solar radiation, the fraction that is effectively converted) almost cannot be directly or effectively applied due to the low thermal efficiency of the collectors [4].

Therefore, once the consumption is usually not coupled with the solar irradiation daily profile, storage is mandatory for the solar thermal energy application [3]. The properties of the reservoir, on

the other hand, depend on its specific application: house heating require materials able to handle temperatures up to 50 °C, whereas electrical power generation units may have to operate above 175 °C [5]. Thermophysical properties of the material should also be observed, according to its specific destination: the use of materials with higher densities increases the energy storage capacity, reducing the volume of the thermal energy storage system; higher latent heats of fusion improve energy storage density; sensible heat storage materials should have high specific heats; higher thermal conductivities increase both the thermal charging and discharging rates; cheaper price of storage material reduces capital and operational costs; higher chemical stabilities of the storage materials increase life of the energy storage system; and corrosion drastically reduces the life of storage plant containers [1].

Traditionally, the heat reservoirs are manufactured from materials of relatively high costs, such as copper, aluminum, glass, stainless steel, epoxy and steel, graphite composites [1,3], and other metal alloys, including Al-Mg-Zn, Al-Si-Sb, Cu-P-Si, and Cu-Si-Mg [2].

This work proposes a low-cost solar heat reservoir for domestic heat generation comprised of a water tank thermally insulated by means of two different coatings, vulcanized nitrile butadiene rubber foam (NBR) and a metalized polyester layer. The solar collector is based on a poly(vinyl chloride), PVC, ceiling panel coated with carbon black-filled glaze, previously studied regarding their construction, thermal efficiency and natural aging [6–8]. The system design is cost-effective because of all of the parts involved in the solar heating are made from commodity plastic materials. These plastic components present wide commercial availability and are easily handled, so that they can be rapidly assembled to build the entire system. Therefore, the solar heating system is simple, modular and easy-scalable, and may be even self-manufactured by the final user.

2. Materials and Methods

2.1. Low-Cost Solar System Fabrication

The low-cost solar heat system was fabricated with widely available commercial materials, usually obtained in hardware stores specialized in construction and hydraulic devices and accessories [9–16]. Basically, the heat reservoir consists of a 100 L-water tank (cylindrical) made of medium density polyethylene (MDPE), from Fortlev, commonly used in building. The tank is double-coated with two polymers: an elastomeric closed-cell foam insulation (butadiene acrylonitrile rubber, NBR), covered by a metalized polyester layer (total thickness of 10 mm), from Armacell. The coating is responsible for enhancing the heat transfer resistance and, therefore, for maintaining the water in a suitable temperature. Water from an external source is introduced close to the bottom of the tank, avoiding the generation of turbulence. This entrance is positioned close to the outlet of cold water for the solar panel collector. It is also useful for keeping the tank temperature stable, avoiding the degradation of the polymeric materials.

The tank is located in a higher position towards the collector, so the gravitational potential difference is responsible for transporting the cold water from it to the solar panel collector. This collector consists in a PVC ceiling panel (1.25 m length and 0.62 m width, from Confibra), commonly used for dropped ceiling in modern constructions, and it is featured by a series of internal divisions in the overall cross-section, shaping 60 longitudinal channels. The PVC panel was coated with a selective black paint (a glaze filled with carbon black) that increases the absorption of sunlight radiation. The water flows through the internal channels of the PVC panel by natural convection or thermosiphoning, without mechanical aid. As the water is heated (density is lowered), it tends to rise to the tank, while cooler water flows in to take its place at the bottom of the collector. Since water flows along the full width of the panel, the heat transfer is highly efficient. Indeed, the measured thermal efficiency of the PVC collector was 67%, even without glass cover. It is very close to the conventional solar collectors' efficiency (around 70%), which contain metallic tubes spaced along the absorber fins [7].

The PVC solar collector did not have a transparent cover (glass) for heat trap (greenhouse effect), like conventional solar collectors. This was intended to avoid water temperature rise due to an

excessive solar heat absorption, what could destroy the system (the temperature could go over the PVC glass transition, 70 °C).

The temperature of the hot water in the reservoir (at its surface) and the environmental temperature were measured using T-type thermocouples, and the information was transmitted to a data acquisition unit (NAP-7000D–ICP COM, from SDC). The full setup is summarized in Figure 1.

The low-cost solar heating system applies no pumps and all tubes and connections are made of PVC, so it has the social function of benefitting especially low-income houses, institutions and families. The totality of the necessary components for its fabrication, their costs in Brazil, and the comparison of the assembled system to a commercial solar heat equipment comprised of a reservoir in stainless steel AISI 304 and copper collector [17] are show on Table 1. The costs are from Brazilian stores using the local exchange, BRL, and the prices were also converted to USD by simply applying the financial market exchange rate on 12 March 2020, 1 USD = 4.79 BRL [18].

It is interesting to notice on Table 1 that the proposed system presents a cost ~70 % lower than the commercial equipment. This economy could be even superior by choosing suppliers or manufactures of the tank or of the double-coating with lower selling costs.

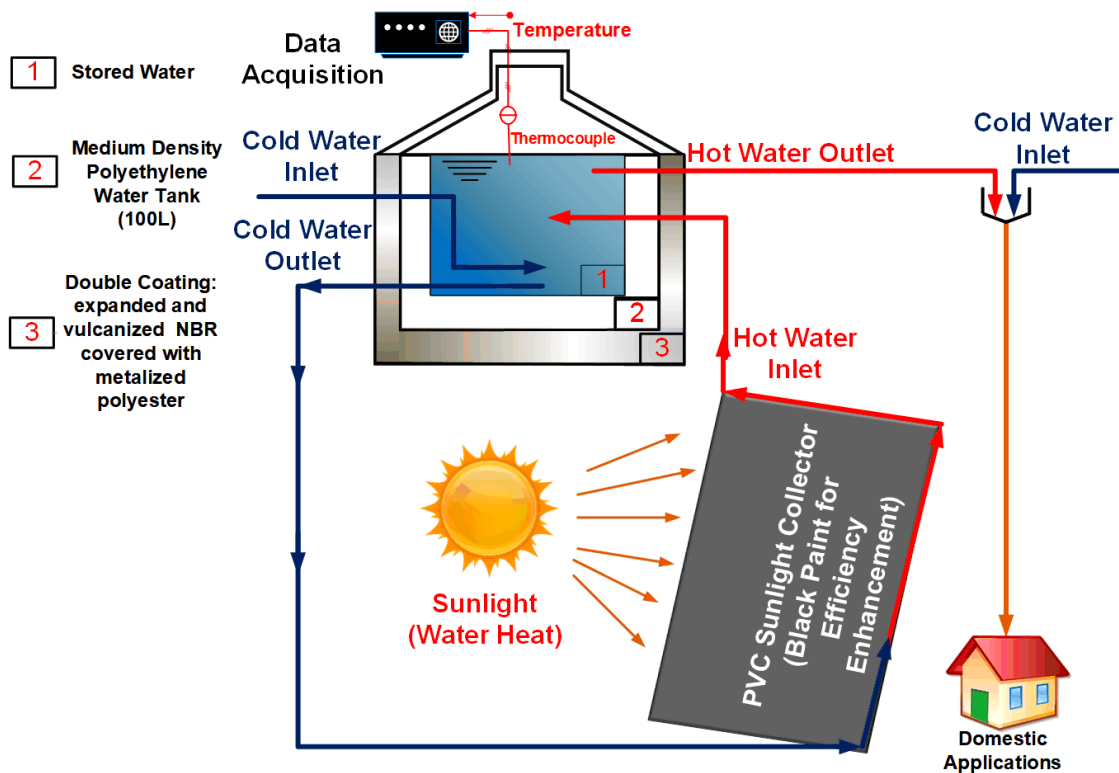


Figure 1. Full setup of the low-cost solar heating system based on the double-coating of the water tank (heat reservoir) and coating of the PVC panel (sunlight collector), for domestic use.

Table 1. Components for the low-cost system fabrication and comparison to a commercial solar heating system.

Component	Cost (BRL)	Cost (USD)	Total Required	Total (USD)	Source
Water tank (100 L)	133.90	27.95	1	27.95	[9]
PVC panel (solar collector) of 0.78 m ²	28.90	6.03	0.78 m ²	6.03	[10]
Black paint (225 mL and yield of 5 m ²)	11.90	2.48	0.78 m ²	2.48	[11]
Coating of NBR and metalized polyester (1 m ² , thickness: 10 mm), plus adhesive	156.75	32.72	1 m ²	32.72	[12]
PVC tubes (3 m, diameter: 32 mm)	24.90	5.20	6 m	10.40	[13]
Weldable sleeve (diameter: 32 mm)	2.79	0.58	2 units	1.16	[14]
Sliding sleeve for weldable pipe (diameter: 32 mm)	28.99	6.05	2 units	12.10	[15]
Weldable union (diameter: 32 mm)	18.99	3.96	2 units	7.93	[16]
Total low-cost system (100 L)	493.77	100.77	-	-	-
Commercial solar heat system (100 L, reservoir in stainless steel AISI 304 and copper collector)	1598.00	333.61	-	-	[17]

2.2. Performance Analysis of the Double-Coated Heat Reservoir

The water temperature inside the tank was monitored along 12 h (from 6 p.m to 6 a.m.), while the outside temperature was simultaneously recorded.

The results of the water temperature were compared to numerical simulations performed by the software ArmWin Professional Insulation Thickness Calculator (Armacell, Capellen, Luxembourg) [19]. This software is based on ISO 12241:2008 [20]. It applies an internal heat transfer model based on the assumptions that a liquid is stored inside a cylindrical tank containing a thermal insulation material. Some parameters are present in the software's database, but others are supplied by the user. They include: thermophysical properties of the liquid, of the tank and of the insulation (*e.g.*, viscosity, density, specific heat, and thermal conductivity), and volumes, thicknesses, and the external heat transfer coefficient. Given an initial liquid temperature, the software generates the temperatures of the stored liquid over a definite interval of time.

3. Results

Due to the presence of tubes and connections, the area effectively used of the panel for collecting the sunlight decreases from 0.78 to 0.75 m². Figure 2 shows two assembled systems with the coating put outside, making the metalized layer visible. There are no connections for allowing the domestic use of the water, since both systems are only prototypes for testing purposes.



Figure 2. Two low-cost solar heating systems assembled (100 L each): PVC solar collector and hot water reservoir with thermal insulation (polymeric coating) outside the tank.

Figure 3, in its turn, shows the overnight temperatures (6 p.m. - 6 a.m.) assessed for the hot water inside the reservoir and for the external environment, as well as the water temperatures estimated by the simulation.

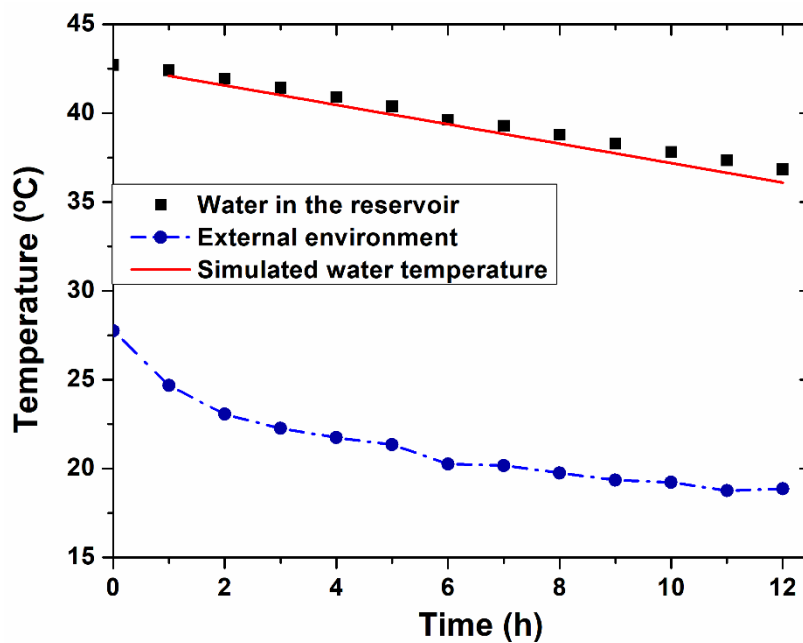


Figure 3. Experimental and simulated data for water temperatures collected overnight (6 p.m. – 6 a.m.), and the correspondent environmental temperatures.

4. Discussion

The results shown in Figure 3 reveal that the system is capable of maintaining the reservoir approximately 18 °C above the air temperature even during the coldest moment of the day after.

The water inside the tank goes from ~42.7 to 36.8 °C as the environmental temperature drops from ~27.8 to 18.9 °C during 12 h. The simulated results obtained by the ArmWin software described fairly well the experimental data, with deviations not superior than 1.9 %. It indicates that the experimental prototype was very well assembled and takes full benefit of the intrinsic properties of the insulation coating. On the other hand, since the experiments showed results slightly superior than the simulations, it is possible to conclude that the system's efficiency is close to the theoretical limits, with no unpredicted heat losses.

It is interesting to compare the assessed temperatures with the ones verified when evaluating commercial solar heat systems. It is known that, for low temperature applications, water is the best heat storage media, due to its high specific heat, non-toxicity, low cost and high availability, but with the disadvantages of presenting high vapor pressure and corrosiveness. For domestic uses, water must be typically between 25 to 90 °C [1]. The reservoirs for systems designed for providing industrial heat or for the operation of solar power plants, in their turn, may operate with water, other liquids, or even with solid materials, and work under much higher temperatures, from 200 to more than 300 °C [21,22].

In particular, the commercial solar heat storage units applied to domestic applications are usually designed for keeping the water temperatures slightly lower than 100 °C when submitted to conditions of maximum sunlight collection [1,20]. Such high temperatures are incompatible with the use of unplasticized PVC. That is because this polymer presents glass transition temperature T_g (under 1 bar) on the order of 75 °C and maximum continuous service temperature of 60 °C [24].

Thus, it is unviable to operate the traditional systems with such low-cost materials, leading to an increase on the cost of fabrication: as previously shown when analyzing Table 1, the PVC-system presents a cost ~70 % lower than the commercial equipment. Once polypropylene homopolymer (PP) presents maximum continuous service temperature of 100 °C [24], it could be an alternative to PVC panels and also to MDPE water tanks for domestic solar heating system. However, despite the fact that PP is one of the most widely produced commodity plastics, there is no large-scale availability of all made PP water tanks and ceiling panels to compete with the cost-effective construction materials made of PVC for low-cost solar systems.

Finally, the very high temperatures are unpleasant to human skins and are inadequate to domestic common uses like taking a bath. Therefore, when using the commercial solar heat systems, there is another increase of costs related to the need of installing a high-performance thermostatic water mixer for correcting the final temperature. In Brazil, this kind of equipment for promoting the adequate mixture between the hot and the cold water sources may present costs as high as 1,314.04 BRL = 274.33 USD [18,25]. This would represent an increase of 82.2 % on the final of cost of acquisition of the commercial solar system.

5. Conclusions

A low-cost solar energy reservoir for domestic heat generation was demonstrated. It is made of a water tank thermally insulated by NBR and by a metalized polyester layer. The tank is coupled to a PVC panel coated with carbon black-filled glaze for enhancing the sunlight absorption. Both the collector and the coating materials are widely available and are easily handled, providing a simple and easy-scalable system that may be even self-manufactured by the final user. The temperature results collected over 12 h (overnight) showed the high efficiency of this system, which is able to maintain the water approximately 18 °C above the environmental temperature even during the coldest moments of the next day.

This system is especially destined to the social function of benefitting low-income houses, institutions and families. As demonstrated, the estimated economy of fabricating it is almost 70 % of the costs necessary for acquiring a commercial solar heat equipment.

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