EXTENDING THE FUNCTIONALITY AND EFFICIENCY OF ENERGY STORAGE TANKS IN SOLAR POWER PLANTS

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Abstract

Improvements to the efficiency of Solar Power Plants are a key objective as the technology matures. One opportunity yet to be explored involves energy harvesting from hot components located within the power plant, utilizing waste heat. We describe two approaches to energy harvesting in this context. These are based firstly on TEC device technology, where we describe the use of both commercially available components and our work to develop more efficient TEC devices based on nanostructured oxides. Secondly, we describe an alternative thermomagnetic approach based on nanoparticle ferrofluids for thermal scavenging and the conversion of heat to usable electrical energy. For both approaches we present concept designs for the harvesting of waste heat from thermal energy storage (TES) tanks, in order to demonstrate the potential of the technology.

Keywords: Energy harvesting, Thermal storage

1. Introduction

Solar thermal power plants include provisions for heat storage, whereby energy collected during periods of abundant insolation can be stored – to be used as needed during sunless periods. In current state-of-the-art parabolic trough solar power plants this energy storage is achieved by the containment of hot fluids (most often molten salts or oils) in either one (hot) or two (hot and cold) multi-layer insulated carbon steel storage tanks, of the type prevalent in the petrochemical industries (see Fig 1 below, for example). Inorganic molten salts are the preferred storage medium, by virtue of their favorable density, specific heat, low chemical reactivity, and cost. There is also the advantage of low vapor pressure, which allows vertical storage tanks to operate at atmospheric pressure.

Fig.1. Andosol 3 Thermal storage tanks

In Concentrated Solar Power (CSP) cost remains a key barrier to full exploitation of the technology. Scaling up existing plants could reduce costs by between 25-35%, depending on DNI. In Southern Europe that would reduce the production cost of electricity to between 13-15c€/kWh, while the higher irradiance to be found in North Africa would reduce the cost further [1]. However, it is clear that there is a continual need to look for all opportunities to drive down costs in order for CSP to be an attractive source of energy on economic and commercial grounds.

The opportunities for novel means of capturing and re-using waste energy form the basis of this paper. In particular we will discuss both novel thermo-electric and thermo-magnetic techniques to harvest energy from thermal storage tanks. The concepts have wider applicability, with potential to transform waste heat from a variety of surfaces within solar power plants into usable electrical power.

2. Energy harvesting from thermal storage tanks

The energy contained in solar power plant thermal storage tanks is predominantly destined for steam generation to drive turbines to create electrical power. However, there is an opportunity to draw off power on demand for low-level but vital plant utilities, such as uninterruptable or emergency power supplies (UPS/EPS). Two techniques are discussed in this section; firstly an approach based on TE converter technology, then secondly a novel thermo-magnetic approach based on nanoparticle ferrofluids. Both techniques are designed to harvest energy [2,3] from retro-fitted conventional thermal storage tanks.

2.1 Thermo-electric converter

There are natural temperature gradients existing within thermal storage tanks that offer the opportunity to use commercial thermoelectric generators to generate useful power. For our example we will consider the temperature gradient that exists across the tank wall and a proportion of the tank insulation. Fig.2. below illustrates the cost of readily available TEC devices, from which an appropriate device can be selected for a given application. For example a 40 x 40 x 3.8 mm device can be found with a quoted output of 82.1W_e at a temperature difference of 72°C. These commercial devices can be ganged and wired together to produce powers exceeding a kilowatt, although additional cooling in the form of water or forced air is likely to be required at very high power ratings. High temperature devices are also available, which can operate at over 200°C for in excess of 200,000 hours.

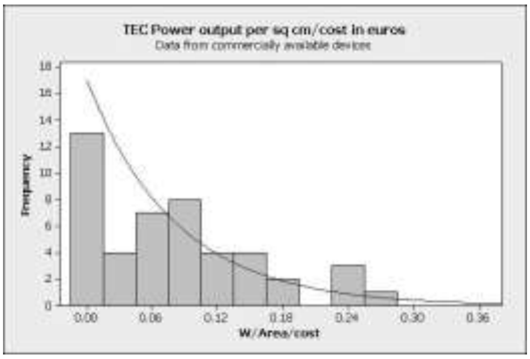


Fig.2. TEC power per unit area per unit cost

Figure 3 (below) shows schematically how an array of TEC devices of the type described above could be interfaced to the outer surface of a TES tank. Depending on the specification of the devices selected, the 2D TEC array is recessed into the tank insulation in order to set the hot face temperature at an optimum value. For high electrical output, forced cooling is likely to be mandatory, but is not shown in the simple case illustrated in Figure 3.

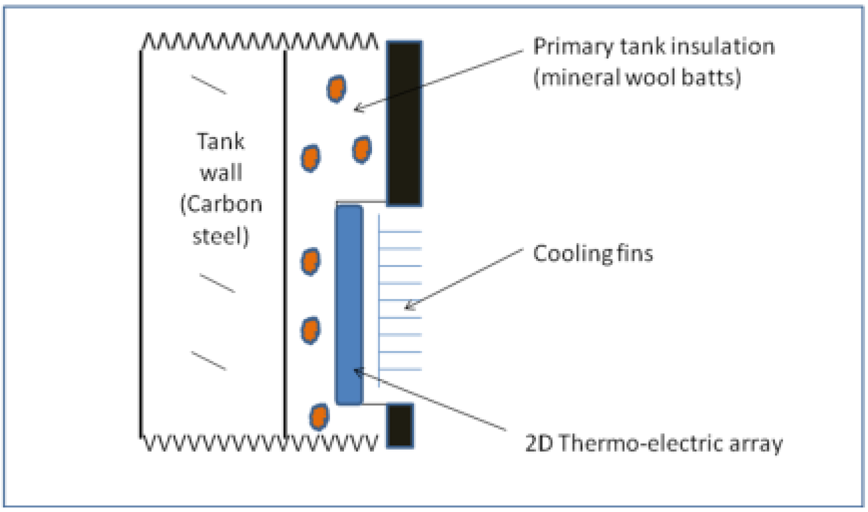
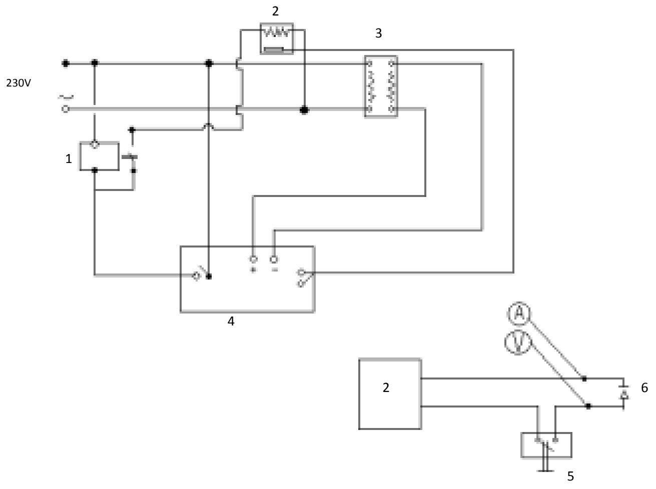


Fig.3. TEC for TES tank energy harvesting (not to scale)

A test rig has been designed and built [4] in order to assess the performance of TEC devices for use in energy harvesting applications, with particular emphasis on the application of transforming heat from TES tanks in solar power plants. The basic circuit is shown in Figure 4, and the unit is currently being commissioned and tested within the Precision Engineering and Nanotechnology Centres at Cranfield University. Additional capability for forced cooling has yet to be added.



Prototype diagram : 1 - contactor; 2- hot plate; 3 – transformer;
4 - temperature controller; 5 - Power On; 6 – 3x LEDs

Fig.4. TEC test station [4]

Commercially available devices have certain limitations, inherent to the materials used. The most common materials used are based on Bismuth Telluride and Lead Telluride. These semiconductors are environmentally unfriendly, expensive to produce, and have a dimensionless figure of merit (ZT) of less than unity. In fact the ZT values of most commercially available devices are relatively small, as shown in Table 1.

Material Group	**Chemical formula**	**ZT Figure of merit**	**Temperature of operation**
Group IV	SiGe	<1	~600 °C
	Mg_2X^{IV} (X=Si,Ge,Sn)		
	$CrSi_2$		
	CoSi		
	$FeSi_2$		
	$RuSi_3$		
Group V-VI	Bi_2Te_3	<1.3	~300°C
	Sb_2Te_3		
	Bi-Sb-Te		
	Bi-Te-Se		
	PbTe		
	Sb-In-Te		
Oxide-based materials	$Ca_3Co_4O_9$ (p-type)	$36 \cdot 10^{-3}$	
	$Na_{0.5}CoO_2$	0.115	
	$Na_xCo_2O_4$ (single crystal)	0.8	800K
	$Y_{0.9}Ca_{0.1}CoO_3$ (p-type)	$1.7 \cdot 10^{-3}$	
	$YCoO_3$ (p-type)	$4 \cdot 10^{-7}$	
	$SrRuO_3$	$1.2 \cdot 10^{-3}$	
	$RuSr_2GdCu_2O_8$	$0.45 \cdot 10^{-3}$	
	$Sr_3Ti_2O_7$ (n-type)	0.012	25°C
	$SrTiO_3$ doped-La	~0.1	
	$(Na_xCa_{1-x})_3Co_4O_9$	1.2	973K
	$Zn_{0.98}Al_{0.02}O$	0.3	1273K
metals	Al	$0.12 \cdot 10^{-3}$	300 °C
	Au	$0.16 \cdot 10^{-3}$	300 °C
	Ni	$17 \cdot 10^{-3}$	300 °C
	Cu	$0.15 \cdot 10^{-3}$	300 °C
Photon-glass, Elektron-crystal (PGEC)	Cs_8Sn_{44}	0.1	~500°C
	$Ba_8Ga_{16}Si_{30}$		
	$Sr_8Ga_{16}Ge_{30}$		
	$Eu_8Ga_{16}Ge_{30}$		
	$Sr_4Eu_4Ga_{16}Ge_{30}$		
	CoP_3		
	RhP_3		
	$CoAs_3$		
	$IrAs_3$		
Te-Ag-Ge-Sb (TAGS)		<1.6	~300°C
Conductive organic materials	Polyacetylene	<0.15	
	Polypyrroline		
	polyaniline		

Table 1. ZT values for a range of commercially available TEC devices [4]

Using the data contained within Table 1, we have selected $Na_xCo_2O_4$ as a material of choice. $Na_xCo_2O_4$ is chemically stable at high temperatures, has a naturally high oxidation resistance, is non-toxic, and has an unusually high Seebeck coefficient at room temperature. This partly compensates for the fact that most oxide thermoelectrics have a low electron mobility, weak mechanical strength, high internal resistance, and high contact resistance between oxide layers and electrodes. We have begun work on the design of a robust process for the synthesis of $Na_xCo_2O_4$. A number of different methods for the production of $Na_xCo_2O_4$ have been reported, including the polymerized complex (PC) method of Ito et al [5], shown schematically in Figure 5.

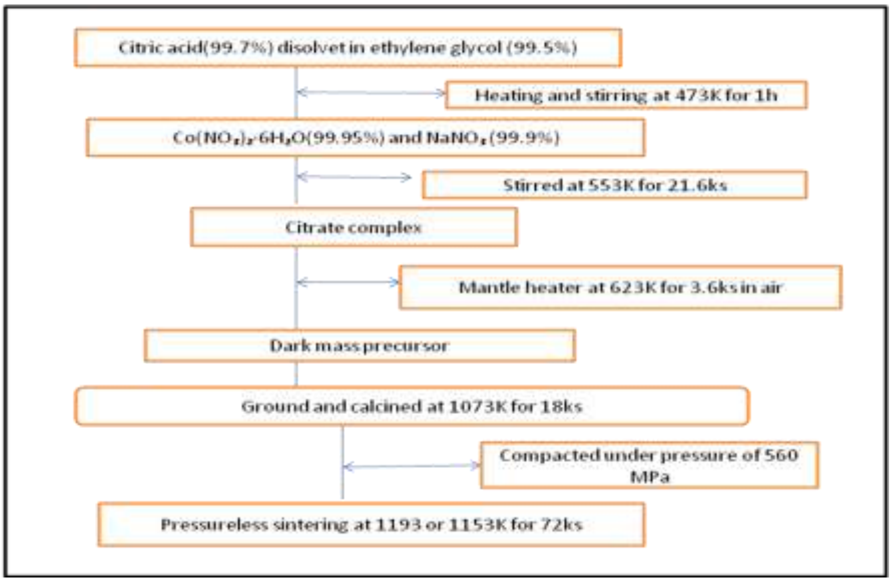


Fig.5. PC method for the synthesis of $Na_xCo_2O_4$ [5]

Current work within the Nanotechnology Centre at Cranfield University is focused on the evaluation of methods for the synthesis of $Na_xCo_2O_4$, the results of which will be reported in a subsequent publication. It is planned to fabricate TEC devices with physical structures similar to those found in commercially available devices, and test the performance of devices using techniques that include the test and evaluation rig shown earlier in Figure 4. 2D arrays of the best performing devices will then be trailled on TES tanks in real or scaled down solar power plants.

2.2 Thermo-magnetic converter, using ferrofluid technology

A Ferrofluid is a colloidal suspension of ferromagnetic nanoparticles held within a carrier fluid [6]. The carrier can be a solvent, hydrocarbon oil or aqueous liquid - dependent on use. Long chain surfactants, for example oleic acid, are used to coat the nanoparticles in order to inhibit flocculation [7]. As the nanoparticles are around 10nm in size they are subject to Brownian motion which keeps them suspended in the carrier fluid. We have synthesized $Mn_{0.5}Zn_{05}Fe_2O_4$ (MZ5) and Fe_3O_4 (Magnetite) nanoparticles by chemical co-precipitation, their subsequent coating with oleic acid, and their suspension in ethylene glycol and heptane respectively [8].

The concentration and type of the suspended nanoparticles, the surfactant, and the carrier fluid combine to impart the overall magnetic and rheological properties of the ferrofluid, most notably the magnetization and base viscosity. This offers the opportunity to tailor the ferrofluid to act in a closed system to provide the removal of thermal energy and its transport into a thermo-electric converter. The unique properties of ferrofluids can be utilized in a closed system, in a suitably arranged magnetic field, to provide power generation from thermal energy, in accordance with eqn.1. below (where ΔP is the pressure differential that drives the fluid into an electro-magnetic induction coil):

$$\Delta P = \mu_0 H \left\{ M(T_{out}) - M(T_{in}) \right\} \quad \text{eqn.1 [9]}$$

In “Proof of Concept“ trials we tested three samples of (i) 200G/200cP magnetite with approximately 10nm nanoparticles in synthetic oil, (ii) 700G/60cP magnetite with approximately 10nm particle size in isoparaffin, and (iii) a 50% mix by bulk volume of the fluids described in (i) and (ii). The results are shown in Figure 6 for an exit speed of 6cm/s for the three Fe_3O_4 based fluids, in both laminar flow and turbulent (manually pulsed) flow.

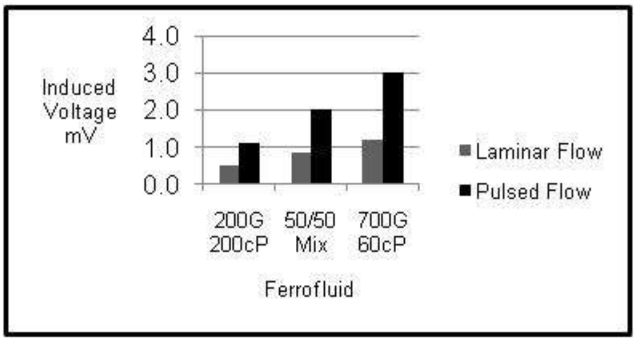


FIG 6. Induced emf voltage : Fe_3O_4 based ferrofluids [10,11]

The induced emfs (up to 3.0 mV in the trial test rig) demonstrate the potential for energy harvesting, provided that the conditions for closed loop thermal pumping can be established. This work is now being exended to design an appropriate ferrofluid for energy harvesting from TES tanks in solar thermal power plants. Further work is also needed to improve the repeatability of the ferrofluid synthesis process, and to develop a set of parameters to fully characterize and test the ferrofluid at completion.

Fig 7 shows two prototype thermal storage energy harvesting concept designs from ‘Peterson Dynamics’. These are not necessarily optimised designs suitable for immediate use in the commercial application but have been designed in order to visualise how the fluid flow systems could work in practice for the given application. The first design shows an arrangement not unlike the TEC device discussed in the previous section. The thermomagnetic cooler section butts up against the TES tank, recessed within the tank insulation in order to ensure that the temperature at the contact point matches the ferrofluid temperature required for maximum fluid flow into the converter section. The converter section, which may also include internal structures to increase turbulence (such as aerofoils), can stand apart from the TES tank and will provide the induced emf into a proximal coil.

The second design in Figure 7 includes the same basic components as those described above, but in this case the entire structure is immersed within the storage tank, perhaps within an additional container. This has advantages for the energy harvesting processes, but adds complexity to the tank design and operation, especially if the tank contains steam generation plant.

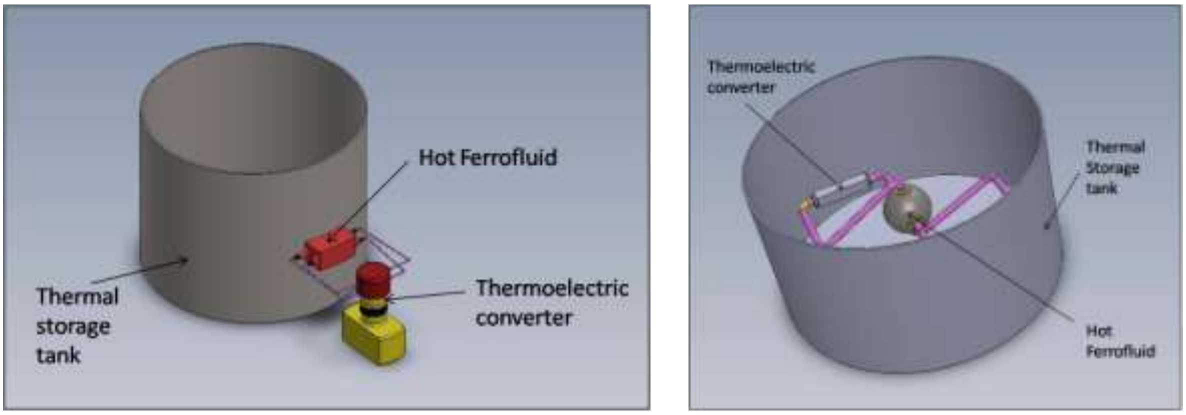


FIG 7. Energy harvesting from thermal storage tank (not to scale) [12]

4. Conclusions

This paper describes the potential for energy harvesting from solar power plants, concentrating initially on the heat stored in TES tanks. We have described two approaches, one based on thermo-electric converters, the second based on a thermo-magnetic effect using nanoparticle ferrofluids. We have described early work on the design of a TEC device, including the use of readily available commercial devices and the development of new technology based on $Na_xCo_2O_4$. For the ferrofluid approach we have presented early results that demonstrate the proof of concept, and have outlined two concept designs for energy harvesting from a TES tank within a solar power plant. Future work will build on these concepts, and broaden out to investigate the potential for energy harvesting from other sources within solar thermal power plants.

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