A COMBINED LATENT THERMAL ENERGY STORAGE AND STEAM GENERATOR CONCEPT USING METALLIC PHASE CHANGE MATERIALS AND METALLIC HEAT TRANSFER FLUIDS FOR CONCENTRATED SOLAR POWER

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Abstract

Cost and volume savings are but some of the advantages offered by the use of latent thermal energy storage. Metallic phase change materials (PCMs) have high thermal conductivity, which relate to high charging and discharging rates in a thermal energy storage (TES) system. In the study a eutectic aluminium-silicon alloy, AlSi12, is identified as a good potential PCM. AlSi12 has a melting temperature of 577°C, which is far above the working temperature of regular heat transfer fluids (HTFs). Sodium-potassium alloy (NaK), also eutectic, is furthermore identified as the ideal HTF in a storage system that uses AlSi12 as a PCM. The researchers furthermore present a concept that integrates the TES-unit and steam generator into one unit. As NaK is highly reactive with water, the inherently high thermal conductivity of AlSi12 is utilised in order to create a safe concept. As a proof of concept, a steam power-generating cycle was considered that is especially suited for a TES using AlSi12 as PCM. The plant was designed to deliver 100MW with 15 hours of storage. Thermodynamic and heat-transfer analysis showed that the concept is viable. The analysis furthermore indicated that the cost of the AlSi12 storage material is 14.9 US$ per kWh of energy storage.

Key words: PCM, AlSi12, NaK, CSP, eutectic, thermal energy storage.

1. Introduction

Solar thermal power generation could be feasible as a source of base load power in arid countries, but due to its intermittent and variable nature, an energy storage system is required. Thermal energy storage (TES) proves to be an attractive and economical alternative for large-scale use. Energy is accumulated in a storage medium, and the storage mechanism can be classified as sensible heat, latent heat, or chemical storage. Considering a review paper by Medrano *et al*. [1], it is clear that almost all operational solar thermal power stations use sensible heat thermal storage. The most popular sensible thermal storage systems use molten salts.

High receiver temperatures are favoured for large-scale power generation as plant maximum thermal efficiency is dictated by the receiver- and condenser temperature of the plant. It is important to consider night time conditions for a high temperature CSP-plant to have a viable and reliable lifecycle. In most of the current concepts for high temperature, concentrated solar power (CSP), a heat transfer fluid (HTF) is used that solidifies at temperatures above ambient. This causes an inherent problem where the solidification of the HTF at night time needs to be dealt with by either using parasitic heating or a method of clearing the heat transfer pipes. Another problem is that, for both latent and sensible energy storage systems, low thermal diffusivity of storage materials impedes the performance of TES-systems.

Latent heat storage materials or phase change materials (PCMs) can store relatively large amounts of energy in small volumes, and thus have some of the lowest storage material costs. Most PCMs operate between solid-liquid transitions, and is therefore most suitable as an indirect storage concept [2]. According to review papers [2] [3] most of the potential salt-based PCMs have low thermal conductivity and extensive material or heat exchanger modifications need to be performed to yield feasible storage systems. This negates the cost savings through material reduction. Birchenall *et al.* [4] propose that eutectic metals may be used to store thermal energy in industrial processes; a concept that has been developed by:

- He *et al.* [5], who developed a waste heat storage device using an eutectic alloy of silicon and aluminium (AlSi12);
- Wang *et al.* [6], who developed a space heater that stores thermal energy in AlSi12; and
- Sun *et al.* [7], who explored the use of AlMg34Zn6 as a storage material.

In this paper a new TES concept is proposed that is aimed at:

- Reducing the cost and volume of the necessary storage material;
- Combining the storage vessel and steam generator;
- Using high temperature heat-transfer fluids (operating at temperatures in excess of 780°C) with melting temperatures lower than 0°C; and
- Achieving high power charging and discharging by utilising PCMs that possess inherently high diffusivity.

2. Material selection

The concept is subject to the nature of the PCM and the HTF, and careful consideration of these properties is therefore important.

2.1. Phase Change Material (PCM)

The rationale for using a PCM in a TES-system include the potential for volume and cost savings [2] and the fact that the inherently high thermal conductivity of metallic PCMs may reduce cost through simpler heat-exchanger design.

As noted by Kenisarin [3] in his review paper on researched and proposed PCM materials, the two most important material properties of PCMs are the melting temperature and heat of fusion of the material concerned. By plotting the melting temperature and heat of fusion of each material on a chart, it is possible to select a PCM with the most favourable characteristics for the design. As thermal conductivity is a priority in the present case, only metallic PCMs were considered in the study. Fig.1 portrays all metallic PCMs plotted with melting temperature on the x-axis and heat of fusion on the y-axis. The arrows indicate the operational temperatures of various collector technologies.

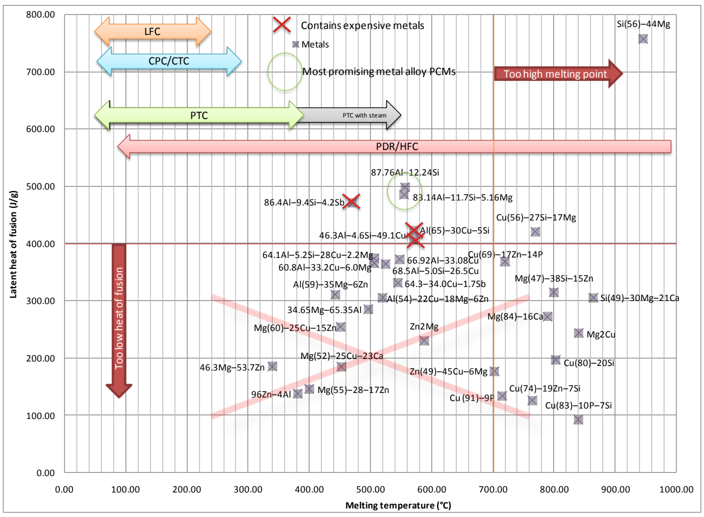

Fig. 1. Metallic phase-change materials with details on the selection thereof.

Using Fig.1 it is possible to identify an eutectic alloy of aluminium and silicon, AlSi12, as one of the best candidate metallic PCMs. It has a heat of fusion of 548.6J/g and a melting point of 577°C [8]. Li *et al.* (8) conducted a study on the suitability of aluminium-silicon alloy as a PCM. They found that aluminium-silicon alloy are relatively stable through multiple heating and cooling cycles; and that having a good eutectic composition and controlling cooling rates may improve stability.

2.2. Heat Transfer Fluids (HTF)

To use AlSi12 as a PCM, an appropriate HTF is needed for the primary heat transfer loop of the power-generating cycle. The HTF should have the following properties:

- Melting point below the night time temperature of a typical CSP-site;
- High thermal conductivity;
- Reasonable specific heat capacity; and
- Atmospheric boiling point above that of the melting point of AlSi12.

As the only HTF that possesses all these qualities, the potassium-sodium alloy NaK was identified for use. NaK is an eutectic alloy of sodium and potassium, and has the following properties [9]:

- Composition: 22% Sodium, 78% Potassium (by mass)
- Melting point: -12.8°C
- Boiling point$_{@101kPa}$: 785°C
- Density: 724 kg/m^3
- Specific heat capacity: 0.879 J/kg.K
- Safety: Reacts violently with water

Regarding the last characteristic, although NaK is very reactive with water, the concept has been developed in a way to ensure that water and NaK will not be in close proximity to each other.

3. Concept

The properties of the chosen materials were the primary driving force behind the storage and steam-generating concept. Two material properties that specifically had a key influence on the concept geometry were the high thermal conductivity of the AlSi12 and the high reactivity of NaK with water. As safety is a very high priority, the high thermal conductivity of the AlSi12 was utilised to yield a concept where steam or water is never brought into close proximity of NaK. The AlSi12 buffers the primary NaK loop from the steam/ water heat-transfer pipes. The AlSi12 acts as a thermal capacitor. Fig.2 portrays a scaled-down cross-section of the storage container to illustrate the concept.

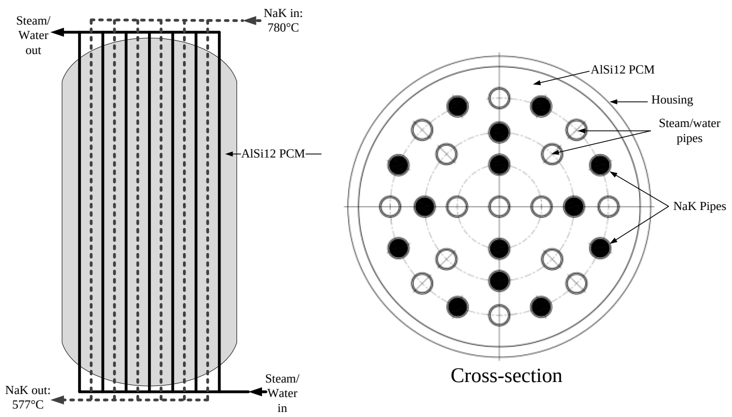

Fig. 2. Cross-section of the storage container showing NaK and steam heat transfer pipes.

The NaK is pumped through the primary heat transfer loop (see Fig.3) where the solar receiver heats it up to 780°C at atmospheric pressure. The NaK is then pumped through stainless steel heat transfer bundles in the thermal storage tanks where thermal energy is transferred to the AlSi12 at 577°C. The AlSi12 is on its melting temperature, and the heat transferred to it from the NaK increases the saturation of the melt. The steam and water pipes also run through the storage tanks and cool down the AlSi12-melt. The superheated steam that is generated by cooling the AlSi12 is then used to drive turbines.

The storage tank is divided into four separate sections, each serving as a distinct part of the steam generator, including:

1. Pre-heater
2. Boiler
3. Superheater
4. Re-heater

This configuration is dependent on the specific power-generating cycle used, shown in Fig.3.

4. Thermodynamic cycle

It is necessary to base the thermodynamic and heat-transfer analysis on representative system boundary values in order to develop a proof of concept. A hypothetical generating cycle therefore had to be designed that would be representative of what will typically be used for such a concept. The analysis is based on the following power cycle (depicted in Fig.3):

- 100MW electrical output;
- Live steam conditions:
  - 540°C superheat
  - 150bar;
- Re-heat conditions:
  - 540°C superheat
  - 30bar;
- Open feed water heater with steam bled from the high pressure (HP) turbine exhaust;
- Intermediate pressure (IP) turbine and low pressure (LP) turbine; and
- Air-cooled condenser (ACC) with a condenser pressure of 0.15kPa.

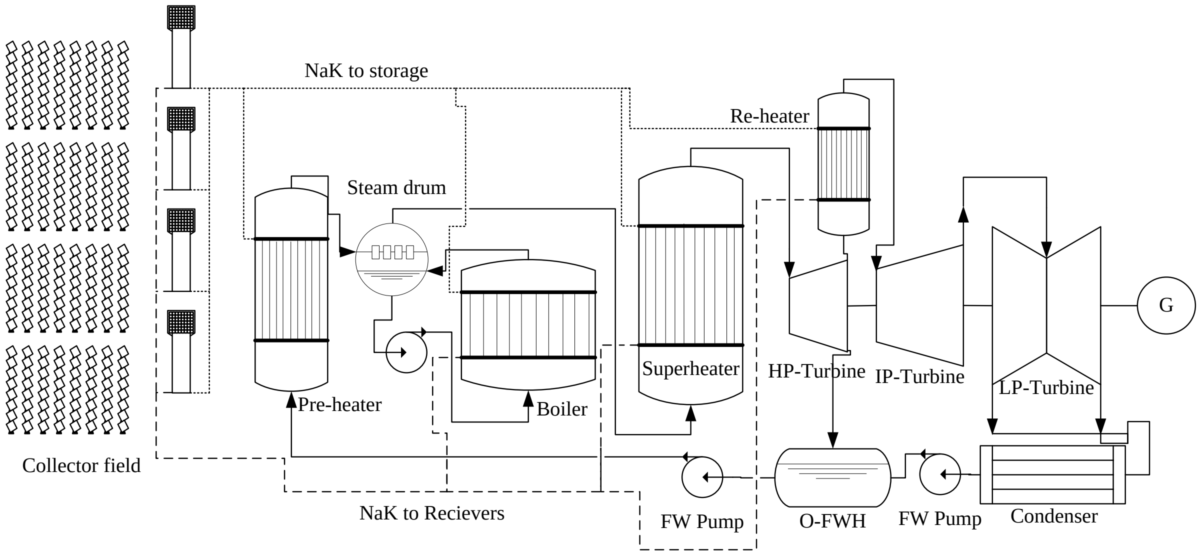

Fig. 3. Power-generating cycle

By conducting an energy balance of the system, the boundary conditions for each of the sub-units (pre-heater, boiler, superheater and re-heater) of the steam generator could be obtained. The steam properties were obtained using the IAPWSIF97 standard. Table 1 portrays the constant power output of the four heat transfer sections in the steam generator in steady state conditions. This can be used to size the storage system and the heat transfer surfaces.

	Inlet enthalpy		Outlet enthalpy		Mass flow rate		Q	
Pre-heater	1008	kJ/kg	1610	kJ/kg	86	kg/s	52	MW
Boiler	1610	kJ/kg	2611	kJ/kg	86	kg/s	86	MW
Superheater	2611	kJ/kg	3423	kJ/kg	86	kg/s	70	MW
Re-heater	3011	kJ/kg	3547	kJ/kg	62	kg/s	33	MW
Total							240	MW

Table 1. Steam cycle boundary values

The isothermal nature of the AlSi12 storage system thermally isolates the energy input (NaK) loop from the cooling loop (water/ steam loop) in such a way that they can be analysed separately. This simplifies analysis. To determine the heat-transfer requirements of the NaK loop, an energy balance was done on the storage material. The energy balance yielded the maximum heat-transfer requirement of the NaK loop. This is presented in Table 2. Calculated heat exchanger efficiencies were used for conceptual analysis.

	Peak input power		Temperature in		Mass flow rate	
Pre-heater	147	MW	780	°C	825	kg/s
Boiler	245	MW	780	°C	1372	kg/s
Superheater	199	MW	780	°C	1113	kg/s
Re-heater	94	MW	780	°C	528	kg/s
Total					3838	kg/s

Table 2. NaK flow requirements at peak power

5. Heat transfer calculations and storage system design

For heat transfer calculations and system sizing, the following thermo-physical properties were used:

- Melting point of AlSi12: 577°C [8]
- Heat of fusion of $AlSi12_{@577}$: 548.6 J/g [8]
- Density of $AlSi12_{@577}$: 2650 kg/m^3 [10]
- Thermal conductivity of :

- ○ $AlSi12_{@577°C}$ 190 W/m.K [10]
- ○ $Steel_{@577°C}$ 39.2 W/m.K
- ○ Stainless steel $_{@577°C}$ 20.8 W/m.K

- Specific heat of $AlSi12_{@577°C\ (molten)}$ 0.897 J/g.K [11]
- Dynamic viscosity of $AlSi12_{@577°C\ (molten)}$: 0.0045 $N.s/m^2$ [11]
- Prandtl number of $AlSi12_{@577°C\ (molten)}$: 0.000021244
- Steam and water: IAPWSIF97 standard throughout
- NaK: Sodium-NaK engineering handbook

All calculations mentioned in subsequent sections are based on these values.

5.1. Storage system sizing

In order for the system to deliver base load power, it should operate the plant at full power (100MWe) for 24 hours a day. The number of hours of energy storage needed is site-dependent but as this is a hypothetical plant, 15hr of storage was selected. By using the boundary values presented in Table 1 it is possible to determine the mass and volume of storage material needed. The results are shown in Table 3.

	Q		Stored energy		Mass		Volume	
Pre-heater	51 519	kW	2 782 035	MJ	5071	metric ton	1937	m^3
Boiler	85 673	kW	4 626 326	MJ	8433	metric ton	3221	m^3
Superheater	69 505	kW	3 753 288	MJ	6842	metric ton	2613	m^3
Re-heater	32 992	kW	1 781 590	MJ	3248	metric ton	1337	m^3
Total	2 39 690	kW	12 943 238	MJ	23 593	metric ton	9108	m^3

Table 3. Required storage material

5.2. Heat transfer model and heat exchanger design

Each of the steam generator sections is dealt with separately to simplify the analysis. The heat transfer characteristics of the NaK heat exchangers are the same throughout. The heat transfer of the water side in the pre-heater, superheater and re-heater are all similar in that single phase convection is the dominant heat transfer mechanism. The heat transfer mechanism of the boiler is exceptionally complex due to two-phase flow.

The heat transfer models of either the water/ steam side or the NaK side are shown in Fig 4. As the Prandtl number of molten aluminium is extremely low, the heat transfer mechanism between the molten AlSi12 and the solid AlSi12 can be treated as purely conductive. In the water/ steam model, the resistance posed by the solidified AlSi12 was based on the largest possible radius of solidified metal around each water/ steam pipe. The NaK-HT model has no solidified AlSi12 as part of its calculation as the NaK heat-exchange pipes are surrounded with molten AlSi12.

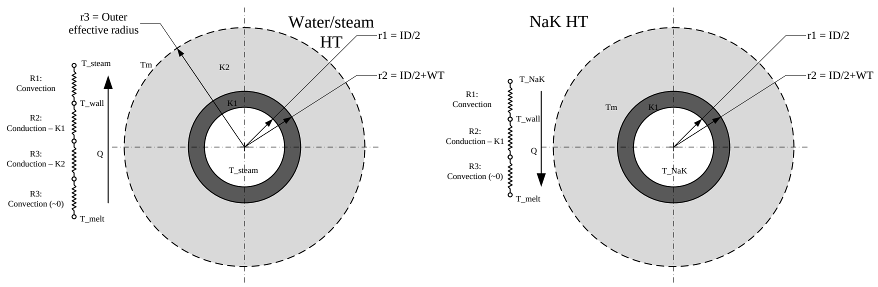

Fig 4. Cross-section through a steam pipe for heat transfer analysis

For the convection of single phase steam and water, the Dittus-Boelter [12] equation was used due to the high Reynolds numbers encountered in the steam/ water pipes. The Lyon-Martinelli equation [9] was used to calculate the Nusselt numbers for the NaK heat exchanger. All steam, water and NaK properties were evaluated at the mean temperature over the heat exchanger ends.

Forced convective boiling is difficult to predict accurately and a number of correlations may be used, each with its own limitations. The 1985 Gungor-Winterton [13] correlation was found to be the most suitable way to predict heat transfer coefficients in the boiler [14]. This correlation attempts to predict the forced convective boiling heat transfer coefficients as a sum of nucleate boiling heat transfer coefficient and convective heat transfer. The nucleate- and convective boiling contributions to the total heat transfer are weighted by scaling factors that are dependent on the local steam conditions. The heat transfer coefficients have to be evaluated at increments of steam quality. The resulting heat transfer coefficient can then be used to calculate the length of pipe needed to reach the next evaluated steam quality; allowing the calculation of the size of the heat transfer surfaces.

5.3. Design geometry

The heat transfer characteristics of the heat-exchange surfaces are highly dependent on the heat exchanger geometry. Smaller diameter tubes and fewer heat exchanger tubes increase the flow velocity and pressure gradient over the heat exchanger. Using a spread sheet it was possible to converge on a design of the heat transfer tube configuration by iteration and using a solver. The pressure drop and heat transfer characteristics of the heat exchangers were the primary objectives. The boiler is designed to deliver 50% quality steam with a mass flow rate of twice that of the live steam. The geometry is presented in Table 4. Note that there are two boilers; this is to limit the diameter of the containment tanks.

		Pre-heater		**Boiler × 2**		**Superheater**		**Re-heater**	
Tank dimensions:	**Height**	21.0	m	8.0	m	24.0	m	17.0	m
	Diameter	11.0	m	10.1	m	12.0	m	10.0	m
	Storage Volume	1987.9	m^3	2552.7	m^3	2698.3	m^3	1318.3	m^3
Steam/Water heat exchanger:	**Tube outside diameter**	38.0	mm	38.0	mm	51.0	mm	76.1	mm
	Wall thickness	3.6	mm	3.6	mm	3.6	mm	3.6	mm
	Number of tubes	35		200		135		160	
	Material	Steel		Steel		Steel		Steel	
NaK heat exchanger:	**Tube outside diameter**	38.0	mm	38.0	mm	38.0	mm	38.0	mm
	Wall thickness	2.6	mm	2.6	mm	2.6	mm	2.6	mm
	Number of tubes	292		1025		345		232	
	Material	Austenitic SS		Austenitic SS		Austenitic SS		Austenitic SS	

Table 4. Design geometry

6. Cost and concept advantages

The cost of the storage material is an important consideration. As the mass of storage material and amount of energy that needs to be stored is known from Table 3, the normalised cost of the storage material can be calculated in US$/kWh. AlSi12 cost 2270 US$ per tonne [15]. The mass of storage material is 23 593 tonne and the energy that need to be stored is 12 943 238 MJ (or 3 595 344 kWh). The normalised cost of the storage material is therefore calculated as 14.9 US$/kWh. Compared to salts that have material costs between five and 20 US$/kWh [16], this figure is competitive. It would, however, be a misrepresentation to make a comprehensive cost comparison based on this value. It is accordingly submitted that a detailed study on the entire plant is necessary for an accurate cost evaluation.

Other advantages of the concept include high receiver temperatures; no solidification of HTFs at night; high charge and discharge rates; and a combined TES and steam generator. The concept may be improved by heating the storage material into the sensible region; thereby increasing its storage capacity. Further improvements are possible by using multiple PCMs and various melting temperatures in a cascading fashion to reduce second-order thermodynamic losses in the boiler and pre-heater, and reducing the NaK flow rates.

7. Conclusion

The use of a metallic PCM offers a number of prospective advantages, including cost savings and high charging- and discharging rates. By making use of a comparative study, it was found that AlSi12 is an effective candidate material for a TES-concept. The potassium-sodium alloy, NaK, was furthermore identified as an ideal HTF for use in thermal storage. NaK does, however, yield an inherent safety risk in a steam cycle due to its reactivity to water. A concept was developed that utilises the high thermal conductivity of AlSi12 to deliver a safe design for a combined TES-unit and a steam generator. Thermodynamic and heat-transfer analysis proved that such a design is feasible, and the cost of the storage material provisionally appears to be competitive with that of solar salts. The full financial benefit that this concept offers above that of salt storage is still unclear as there are a number of factors that need to be considered. Further research in this regard is therefore recommended, particularly if one considers the prospective advantages of this concept. A time-dependant analysis of the concept may furthermore shed important light on the economic feasibility of the concept.

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