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3-A019: Development of High Temperature Phase Change Storage Systems and a Test Facility

Project results and lessons learnt

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Contact name:	Professor Wasim Saman
Title:	Development of High Temperature Phase Change Storage Systems and a Test Facility
Email: Wasim.Saman@UniSA.Edu.Au	**Phone:** (08) 8302 3008
Website:	http://people.unisa.edu.au/Wasim.Saman

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Executive Summary

Dispatchability of electricity supply is providing a serious challenge limiting of the growth of of renewable electricity supply both in Australia and around the world. Concentrated Solar Power (CSP) with thermal storage is a significant and economically viable contributor to redressing this situation. Recent international solar thermal installations have incorporated larger storage capacities. The current two tank molten salt thermal energy storage systems and materials have been the standard installed system. The lack of a test facility for high temperature thermal energy storage development has limited the research effort and the validation of laboratory scale materials and systems research. The report outlines the details the design, installations and opportunities created through the establishment of a world class thermal energy storage facility at the University of South Australia (UniSA). The facility will provide the nessesary equipment and experties to drive research and development into innovative low cost high temperature thermal energy storage systems to reduce the risks associated with utilising new technologies by the solar thermal industry.

This facility was designed to enable the testing of large laboratory-scale prototype thermal energy storage systems for CSP. With a 50kW storage capacity providing a heat source of up to 900ºC, this facility, one of only a handfull in the world, can be programed to subject a test prototype to the full range of flow and temperature conditions simulating the field operational conditions. This provides the ability to assess the thermal efficiency, charging and discharging performance and the long term stability of a prototype thermal energy storage system.

In parallel, the facility has been utilised during the development and testing of new prototype storage systems that use high density Phase Change Materials (PCMs) for compact thermal storage at medium and high temperatures. The testing of the PCM thermal energy storage system prototypes have proven to be valuable. The charging, discharging and storage effectiveness was assesed and novel concepts for improving the performance were able to be tested leading to recommendations for the continued refinement and development of the new systems.

In addition to supplementing current UniSA thermal energy storage programs, the facility will be available to other researchers and industry participants developing solar thermal technologies. The outcomes of this project will directly contribute to developing cost effective, high temperature storage systems to enhance the dispatchability of solar thermal power plants.

Project Overview

Project summary

This project comprised of two components. Initially the project centred around the establishment of a world class high temperature thermal energy storage test facility with a heat supply capacity for storage of 50 kW, for storage temperatures from 150°C to 900°C. This provides researchers and developers with a unique facility to test prototype high temperature storage systems, which, in turn advances research in high temperature storage and bridges the gap between theoretical and laboratory research and field trials. In addition, it has provided the necessary equipment for the high demand for research validation in this area.

The project also involved the design, construction and testing of two thermal storage system prototypes. These incorporated new phase change materials (PCMs) which were developed by UniSA and used innovative techniques that were investigated by UniSA for enhanced heat transfer within the PCM storage system. The aim was to advance the technology and reduce the cost of high storage density, high temperature thermal energy storage systems.

Project scope

Current CSP plants operate by pumping the heat transfer fluid (HTF) from the receiver, where it is heated, through to a high temperature storage tank. This heated liquid is then pumped to a heat exchanger where it exchanges heat with the working fluid of a power station, typically steam. The HTF is then transferred to a cold storage tank before it can be heated again in the receiver. Thermal energy storage is a vital component of any CSP plant. It provides a buffer between the variability and unpredictability of the solar energy source and the requirements of the electrical power station and electrical power output. While many solar thermal energy plants are now operating around the world, the cost and technology development is well behind that of solar photovoltaic generation. However, the relatively low cost of thermal energy storage in comparison with electrical energy storage provides a good solution to the escalating dispatchability issues in locations of high wind and solar penetration such as South Australia. Until it can be demonstrated that thermal energy storage systems have advanced to a stage where they are both technically and economically viable for large scale applications, the proliferation of CSP plants will be delayed.

Until now, there has been no cost-effective compact storage technology available. Most existing thermal energy storage systems currently use sensible heat storage comprising of molten salts or oil stored in hot and cold storage tanks. They require expensive tanks and large volumes of storage materials limiting the economically viable capacity and the dispatchability of electrical power. In this project, PCMs were proposed to be utilized to store energy. PCMs are substances with a high heat of fusion which, melting and solidifying at certain temperatures, are capable of storing or releasing large amounts of latent energy at a suitable temperature. Compared to sensible heat storage, PCMs allow large amounts of energy to be stored in relatively small volumes and for that reason, PCMs have some of the lowest storage media costs of any storage concepts. PCM instability and poor heat transfer between the heat transfer fluids (HTFs) and the PCM need to be overcome before they can be considered a viable high temperature thermal energy storage technology.

There are three known purpose-built thermal energy storage test facilities in the world that have been reported. The University of Lleida in Spain has established a high temperature thermal storage test rig. It has a heat capacity rating of 22 kW and can test storage systems up to 400°C. Plataforma Solar de Andalucia has a similar system but much larger facility. The other facility is located at the German Aerospace Center (DLR) in Stuttgart, Germany. While this plant is for testing just PCM based systems, the DLR has been considering to expand this system to enable molten salt based systems to be tested.

With most manufacturers and suppliers opting for using solar tower technologies and the associated gains in thermal efficiency and rise in operating temperatures, it became necessary to develop higher temperature and more economical storage systems. UniSA proposed to establish a world class high temperature thermal energy storage test facility to support solar thermal technology development. This facility is capable of simulating a solar energy supply source in terms of temperature and volume fluctuations and to test the effect of this fluctuation on the thermal energy storage system performance. While the facility was designed initially to support UniSA's research program for testing PCM thermal storage systems, the capacity to use it to test sensible heat based thermal storage systems and also for life-cycle testing of components designed to operate at high temperature and other applications where a controllable high temperature heat source is required was a key design consideration.

The development of a testing facility within Australia provides a channel for researchers to develop their technologies from theoretical and laboratory scale research and experiments for proof of concept, to important mid-scale prototype testing. This scale of prototype testing is an economical approach to demonstrating the viability and to go some way to de-risking thermal energy storage technologies. The lessons learnt in the prototype scale tests can be integrated into full scale field demonstrations at a fraction of the cost. The knowledge gained in the design and construction of the test facility in conjunction with the partnership with the local and international partners shall provide a base for a world leading knowledge bank in the high temperature storage sector.

UniSA has been carrying out work relating to maximising the heat transfer rate into and out of PCMs for low temperature applications along with leading international researchers in the PCM field through participation in the International Energy Agency task 42. UniSA has developed considerable intellectual property (IP) in this area. UniSA has patented work in this area and expects to develop further patents in the future. This test facility was devised to allow UniSA to apply some of these technologies to high temperature systems to investigate their suitability and to develop and test laboratory-scale high temperature PCM thermal energy storage prototypes for CSP plants.

Outcomes

Test Facility Design

The Initial project began in April of 2012, centred around the establishment of a world class high temperature thermal storage test facility with a heat supply capacity of 50 kW for storage temperatures from 150ºC to 900ºC. In addition to consultation with local and international organisations including VastSolar, delegates from UniSA visited the University of Lleida to view their newly constructed high temperature test facility and participated in discussions in regards to the design of their system and the test facility to be constructed at UniSA. They learnt of their experiences and recommendations for the test facility proposed at UniSA. University of Lleida delegates also visited UniSA to review the designs of the test facility and had discussions with the design team regarding the proposed test facility. In June 2013, UniSA staff also visited two of the international industry partners for this project – The German Aerospace Center (DLR) and Novatec Solar, both in Germany.

A design committee was established within UniSA and with the continued support of industry partners, a number of different design concepts using different types of heat transfer fluids were investigated and reviewed. From this work it was concluded that air at ambient pressure was the best option from a point of view of cost and safety. Detailed design calculations were produced for two different arrangements of the test facility using air as the heat transfer fluid. A detailed costing and work health and safety (WHS) assessment was concurrently carried out for the two options. The two detailed quotes received from two potential equipment suppliers (one which operates on natural gas fuel and the other on electricity) were assessed considering capital cost and operating costs, energy and building infrastructure requirements, WHS issues and testing requirements. The system with the electrically powered heat source was selected and approval from the University for the upgrade of the electrical infrastructure was granted and implemented to facilitate the installation.

The test facility was installed in the Mechanical Engineering Laboratory at the Mawson Lakes Campus, UniSA with the following performance criteria:

- Heater module with variable output power up to 200kW (415 VAC 3 Phase supply)
- Air flow variable up to 500 lt/sec (STP)
- Fan exit pressure up to 600 Pa.
- Operating temperature up to 900° C
- Pressure sensors accuracy < 1%
- Temperature sensor accuracy < 1%

The facility consists of the following main components:

- Blower skid
- Heater assembly
- Turning ducts
- V duct
- Storage system table
- Prototype packers

- Exhaust duct
- Control system

Figure 1 and Figure 2 Show the High temperature test facility layout.

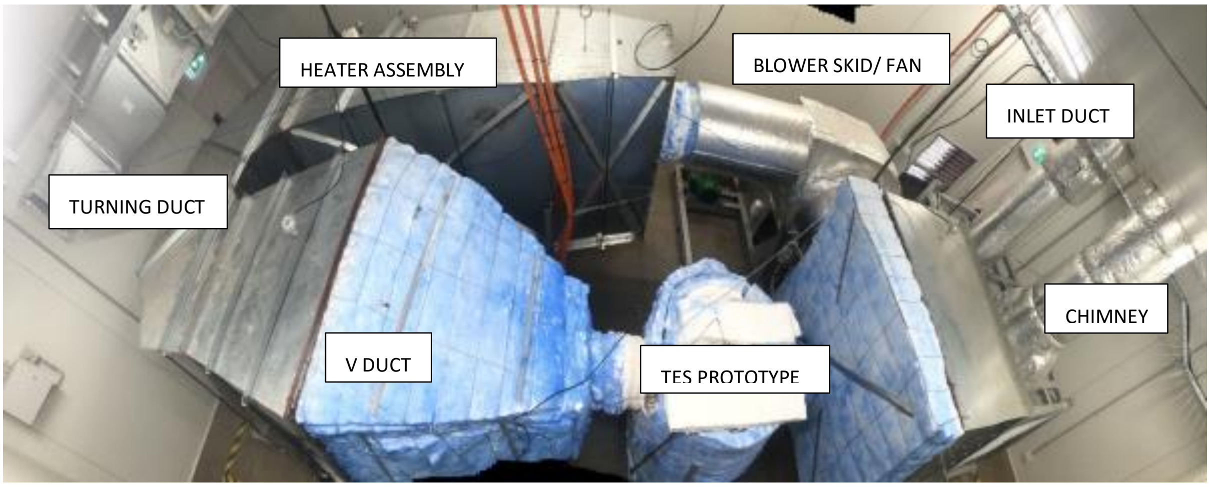

Figure 1 Top view of test facility

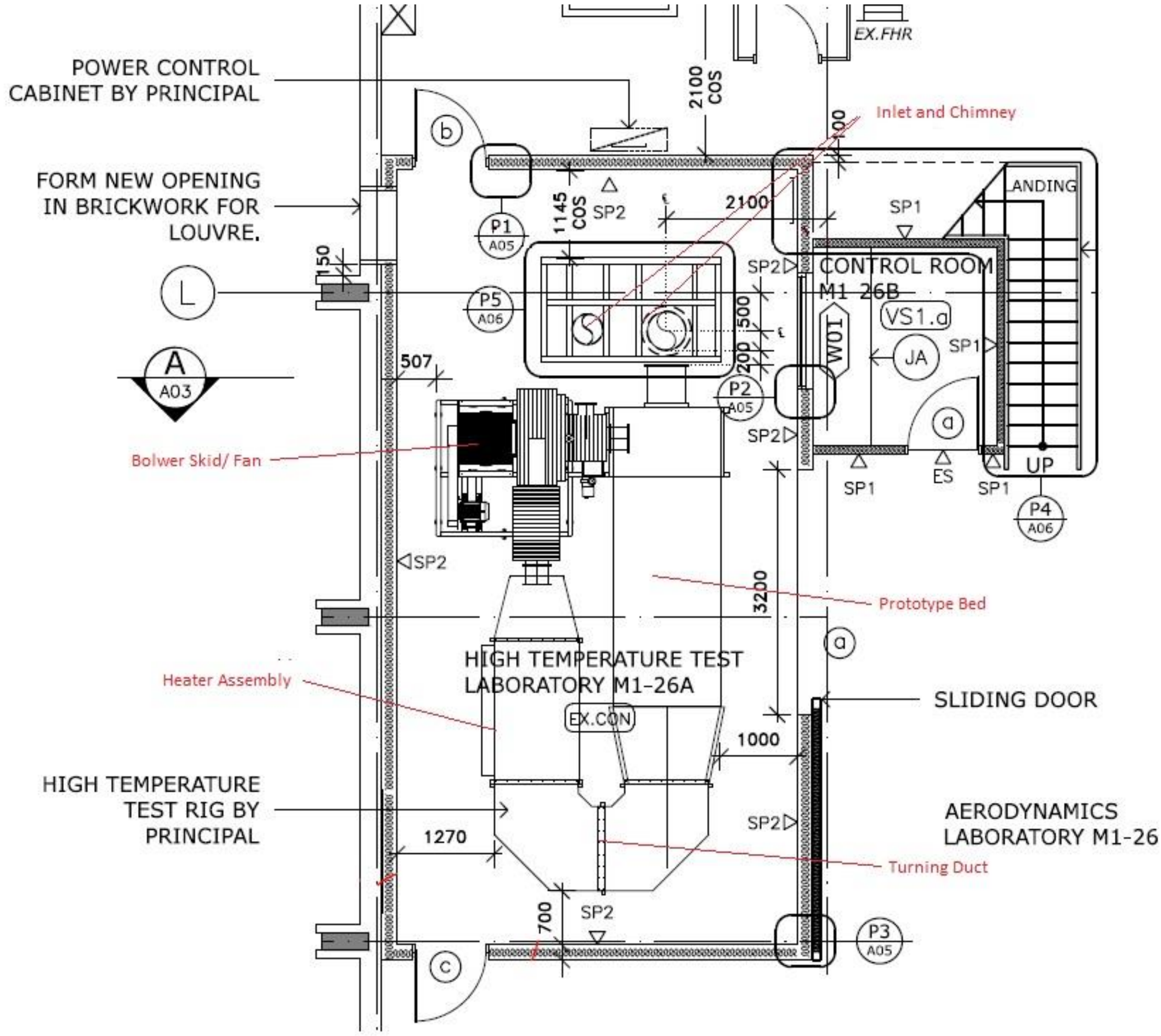

Figure 2 Schematic of the Prototype Loop

Blower Skid

This assemble includes a standard blower unit (rated to 500lt/sec at 600 Pa and 900°C. The fan motor is controlled via a variable speed drive.

Heater Assembly

The heater assembly (Figure 3 is a section of duct with electric elements in it. A nominal 200kW of heating power is provided. The elements are wire coils and supported on ceramic tubes. The element assemblies are inserted from one side to make changing an element possible. The elements are rewired back to the control equipment adjacent to the unit.

Figure 3 Construction of the Heater Bank.

Turning Ducts

There are two turning ducts at the end of the rig. The turning ducts are on castors so they can be moved when inserting a PCM prototype. They all have the standard flange interface to the next piece (1000h x 600w flow area, flange 1400hx1000w Inside x 50 wide). When inserting or removing a PCM module the flange joint to the heater is disconnected (or loosened), the system to be tested is rolled into place and the flange connections to the heater and PCM are clamped up.

Note that the system is not completely sealed. It will leak at flanged joints, between the joints in the duct, i.e. along the corners of the duct, at the element insertion holes and at the access holes. The leakage was expected to be minimal.

All duct items in the system have 200mm of ceramic fibre insulation on their internal walls. This fibre is installed "side on" so that the edge of the fibre sheets are exposed to the internal air. This surface is sprayed with a product that soaks into the surface and stiffens the surface. The surface is then capable for operation up to 1400°C and 14m/sec air flow.

V Duct

This duct takes the air from the turning duct and into the PCM prototype. It is 1000 mm long and connects the turning duct flange (1000h x 600w flow area, flange 1400hx 1000w inside 50 wide) to the standard flange connection (1000h x 1000w flow area, flange 1400hx 1400w inside 50 wide). It is on casters so it can be moved while inserting a module for testing.

Storage System Table

Since the prototype storage systems will vary in size and may be too heavy to push around, the PCM section of the rig is a steel table. The prototype to be tested can be placed on the table and any required packing ducts inserted to fill the gap between the V Duct and the heat exchanger. Allowable lengths for the systems to be tested are 500, 1000, 1500 or 2000 mm.

The design of the prototype to be tested must be such that when on the table the flange faces line up with the heat exchanger and V Duct flanges (1000h x 1000w flow area, flange 1400hx 1400w inside 50 wide).

Prototype Packers

These are sections of duct that allow smaller prototype units to be installed in the rig. Two are 500 mm long and two are 1000 mm long. The two 1000mm long packers are tapered and taper from 1000h x 1000w flow area to 600 h x 600w flow area. They bolt up to the prototype and the V duct or heat exchanger inlet. Allowable prototype lengths sizes are:

1000mmx1000mm flow area: 3000, 2500 or 2000mm long

600x600 flow area: 1000 or 500mm long

Exhaust Duct

This is a section of duct that bolts to the outlet of the prototype.

Control System

The control system uses three variables as inputs: heater power, bypass valve opening and fan speed that can be adjusted. These variables are delivered into a HMI unit (Figure 4) that is programmed to:

- Adjust the fan speed to a fixed rate
- Automatically adjust the fan speed to achieve a set flow rate (based on the pressure difference across the prototype)
- Automatically adjust the bypass valve and heater power to achieve a set the prototype inlet temperature.

Figure 4 Control Room

The air flow rate and temperature are controlled via PID loops in the HMI. Initially the process values for these control loops are the inlet temperature to the PCM and the pressure drop across the prototype. The target inlet temperature to the prototype and the target pressure drop across the prototype and the HMI are set and control the heater power, bypass valve and blower speed to achieve this.

Included in the control system are over temperature protectors for the heater unit and an interlock on the extraction fan. The HMI is located in the control room and a control panel on the rig manages safety interlocks and the like.

By March 2015, detailed drawings of components of the high temperature test facility were completed. These showed that the original test rig design was too large for the designated floor plan area. As the area could only be extended by about 1 metre, the test rig design needed to be shortened. The test rig design was modified to incorporate recirculation of the heat carrier fluid (air). The new design of the rig was improved, more than 1 metre shorter, and also more energy efficient and gained the ability to heat up faster so that tests could commence in a shorter period of time. The modified layout and design was approved by UniSA’s Facilities Management Unit and all WHS issues considered. Purchase Orders for the construction of the equipment was submitted to Ecefast and AirEng, and detailed drawings of the modified test facility components were completed and construction got underway.

PCM Thermal Energy Storage Prototypes

Two postgraduate students were involved in this project. A PhD student was involved in the development of a prototype storage system using PCMs. An extensive literature review on high temperature PCM storage systems was conducted. A Masters student was involved in the design of the high temperature test facility.

The PhD student created and modified the numerical computer model for a PCM thermal storage system incorporating fins and heat pipes and extended the thermodynamic and fluid dynamic equations in the heat pipe for better prediction of the thermal performance of the storage system.

Commencement of Testing

The facility was installed and commissioned in March 2016 (Figure 5). During testing of the first prototype at high temperature, a fault occurred in the heater bank of the test rig which needed to be rectified by the manufacturer. The high temperature test facility was recommissioned by 20th May 2016 and has proven to operate at temperatures up to 900°C.

Figure 5 Construction Finalised, Ready for testing, March 2016

The test facility has been used to test two laboratory-scale PCM prototypes. Initially, melting and freezing testing was completed for the PCM 308 prototype. These results clearly showed the PCM melting and freezing. The aim of the testing for prototype 308 was to investigate the effectiveness during the discharging process. The design of the prototype applied the innovative U tube design which was found capable of delivering higher heat transfer rates during discharging. Maintaining a high effectiveness throughout the discharging process is necessary to maximise the amount of energy that can be usefully extracted from the PCM. The discharging process is the most critical as this process determines the efficiency of the power block and prevents fluctuation of the operating conditions and power output. The test results showed that the effectiveness is maintained and does not dramatically decrease. This result confirms that the U tube design achieved the required outcome. Furthermore, the result is consistent with the E-NTU model developed by UniSA which is based on ideal heat transfer analysis. This not only confirms that the heat transfer was effective but also that the model can be used as a design tool, which simplifies the techno-economic analysis process. This can be applied to any PCM system based on molten salt. This work provides confidence in continuing the work on PCM energy storage.

Figure 6 Prototype 638 in the Test Facility, ready for testing.

Melting and freezing tests were also completed on the PCM 638 prototype (Figure 6). Considerable research had been conducted on this PCM at small scale, with a volume of approximately 10 mL. The aim of this testing was to demonstrate that this PCM can melt and freeze, (Figure 7) at a larger scale with phase change. The temperature results showed that the PCM did melt around 638 °C with phase change occurring during the freeze test. Note that the temperature measurements do not match the freezing temperature as they represent local measurements and are influenced by the temperature of the surrounding PCM. This prototype test did not focus on the heat exchange effectiveness, and therefore it was expected that the heat transfer to the heat transfer fluid would be poor. Therefore the potential of this PCM to be used at scale has been demonstrated. Future testing will involve cycling to further validate the viability of the PCM at scale.

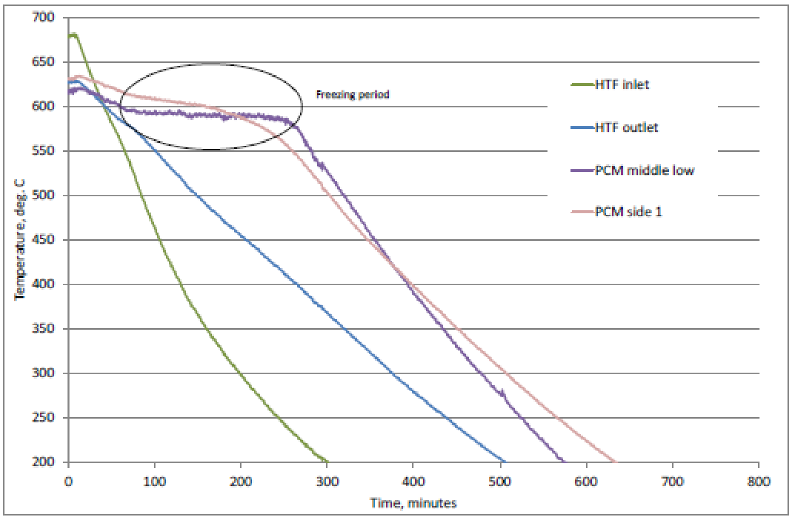

Figure 7 Freeze test data for Prototype 638 using air as the HTF.

Transferability

With increased interest in storing thermal energy at high temperatures for CSP and other industrial processes, there is a growing need to test prototype scale systems. This facility provides the means to determine the thermal characteristics of systems requiring a high temperature heat source up to 900°C. One of only a handful of facilities globally, it was developed to provide industry and research institutions with a testing service needed to support the development of high temperature thermal energy storage but its versatile design means that it can be used for a variety of industrial processes. Other industries that can utilise this facility include but are not limited to conventional power generators and industries working at high temperature, e.g. steelworks, mining, mineral processing, glass and cement producers. UniSA has recently secured funding to work with a minerals organisation in using molten salt in high temperature minerals processing.

Furthermore, knowledge was developed into effective design of tube in shell PCM thermal storage systems which enhance the techno economic performance of these systems. This research is applicable to all research associated with PCMs. This research is transferrable to other PCM applications including the design of thermal storage systems for industrial high temperature applications and heating and cooling applications.

This research was disseminated through publications and conference presentations, as shown in the publication list. The research work has been transferred to other research projects within the University of SA all in the field of energy storage and both the facility and research outcomes will be extensively used in our continuing research into reducing the cost and technical risks of new thermal storage systems.

Publications

Journal articles

Performance enhancement of high temperature latent heat thermal storage systems using heat pipes with and without fins for concentrating solar thermal power plants (2016) Renewable Energy, 89, pp. 36-50.

Belusko M., Tay N.H.S., Liu M., Bruno F. In Press, Effective tube-in-tank PCM thermal storage for CSP applications, Part 1: Impact of tube configuration on discharging effectiveness, Solar Energy.

SolarPACES 2016

Poster presentation on the high temperature test facility:

Bruno F, Belusko M & Saman W, *A Facility for Testing High Temperature Thermal Storage Systems*

Conference paper which will be presented orally:

Almsater, S., Saman, W., Bruno, F. "Numerical Investigation of PCM in Vertical Triplex Tube Thermal Energy Storage System for CSP Applications".

Intellectual Property: Patents / Licences

There have been no published patents or licensing of technology.

Awards

There have been no national or international awards presented in relation to the project.

Conclusion and next steps

The establishment of this high temperature thermal energy storage testing facility will provide researchers with the means to develop their technologies, allowing them to deliver real world solutions to a knowledge and technology gap. The lessons learnt in the prototype scale tests can be integrated into full scale field demonstrations at a fraction of the cost. The development of the PCM thermal energy storage prototype has continued and additional testing will focus on the long term stability of the system.

The group has begun to market the capabilities on the new test facility. This includes the inclusion of the facility in the 2016 AIRAH Industry handbook, the production of brochures and the conference poster, shown at SolarPACES 2016 in Abu Dhabi to a world market.

Lessons Learnt

Lessons Learnt Report: High Level of Air Leakage in the System

Project Name: Development of High Temperature Phase Change Storage Systems and a Test Facility

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	National

Key learning

The project has identified the importance of the correct sealing of the hot air delivery ducting. The original design of the system was to be not completely sealed. It allowed leakage at flanged joints, at the joints in the duct, i.e. along the corners of the duct, at the element insertion holes and at the access holes. It was expected that the leakage would not be critical. Due to the relatively low system pressure, the pressure drop over the PCM thermal energy storage prototype proved to impart a significant back pressure on the system which dramatically increased the air leakage throughout the system. The high air leakage percentage that ensued lead to a poor test system efficiency, high ambient test chamber conditions and put a strain on the heater bank sealing contributing to a required redesign of the electrical heater bank.

Implications for future projects

Any future redesigns of the test facility will look to ensure the system is fully sealed and material selection and component connectivity more stringent controlled. The design of future prototypes will look to minimise the pressure drop across the storage prototype without affecting the storage efficiency.

Knowledge gap

N/A

Background

Objectives or project requirements

For the efficient and safe operation of the test facility it is a requirement that the air leakage from the system is minimised. Due to the chosen construction, temperature range and the component used (especially the high temperature fan and the heating elements) it is not feasible to have a completely sealed system. After testing commenced it became apparent that further work was necessary to reduce the air leakage from the system.

Process undertaken

Initial prototype testing showed that air leakage throughout the system was above acceptable limits. University technicians in collaboration with the construction team set about minimising the air leakage path. Additional structural support as well as alternative sealing methods were utilised to drastically cut the air leakage percentage.

Lessons Learnt Report: The Choice between Electricity and Gas

Project Name: *Development of High Temperature Phase Change Storage Systems and a Test Facility*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Storage
State/Territory:	National

Key learning

This project has demonstrated the benefits of an electrically powered heat supply for prototype testing purposes. The electrical heater bank offers a high degree of control over the energy input into the system. Also, it allows the system to run in a recirculation mode, significantly improving the overall efficiency of the test chamber and increasing the system heat-up time.

Implications for future projects

The design of the test facility using a reliable, highly controllable heat source with the energy efficiency benefits of the recirculation mode made possible by the electrical system ensures that the system can be operated in an autonomous and efficient manner. This opens the facility to numerous applications ranging across a number of industries including power generation, steelworks, mining, mineral processing, glass and cement production.

Knowledge gap

N/A

Background

Objectives or project requirements

This project aimed to create a world class testing facility for high temperature storage capable of providing high quality testing services in a sustainable manner.

Process undertaken

The design process incorporated the close partnership between UniSA and its industry and university partners. Conceptual designs were greatly influenced through lessons learnt from the University of Lleida, The German Aerospace Center and Novatec Solar. Within the University, the vast knowledge of the researchers in the project team and the tremendous support from the University's Facilities Management Unit and chancellery was integral to the success of the construction of the facility. Finally, the interaction with the architects, Wiltshire and Swain and the testing equipment builders- Ecefast and AirEng has ensured that milestones set out for this project were achieved.

Appendix

Keywords

Solar Thermal, Concentrated Solar Power, Thermal Energy Storage, Phase Change Materials, Testing Facility, High Temperature Testing Facility, High Temperature, High Temperature PCM, PCM, PCM storage, Energy Storage, Renewables, Energy Dispatchability, Grid Output Security, Prototype, Prototype Testing, Baseline Power.

Glossary of terms and acronyms

Concentrated Solar Power- (CSP): Technology that harnesses the sun's power to generate heat through the use of lenses and reflectors to concentrate sunlight.

Thermal Energy Storage- (TES): The storing of thermal energy. In the solar thermal industry the storage of thermal energy provides a buffer between the variable solar energy source and the power generation requirements.

Phase Change Material- (PCM): A substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of thermal energy.

High Temperature PCM storage- The storage of energy at high temperatures, $150^{o}C$ to $1000^{o}C$, through the changing of the state of a PCM.