Solar PACES Task III
Thermal Storage
Survey on R&D Activities

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CONTENTS BY KIND OF STORAGE

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Institution	Country
CEA-LITEN	France
CIEMAT-PSA	Spain
CENER	Spain
DLR	Germany
ENEA	Italy
FISE	Germany
IEE-CAS	China
IK4-TEKNIKER	Spain
Masdar Institute	Emirates
SUPSI	Switzerland
TAU	Israel
TECNALIA	Spain
UniZar	Spain

SENSIBLE HEAT STORAGE

CEA – LITEN (France)

FROM RESEARCH TO INDUSTRY

SolarPACES

TASK III-TES

Regenerative Storage

Challenges:

- Relatively low storage density,
- Differential dilatation between storage media and envelope=> mechanical stability of design in the case of unstructured solid materials,
- Regenerators are widely used in steel and glass industry, but only a few pilot TES units are tested for CSP applications (in Central Receiver Systems with atmospheric air receivers)

State of the art:

- Regenerators are widely used in steel and glass industry.
- Pilot TES units are currently tested in power towers with atmospheric air receivers.

Concept approach:

Low cost and robust regenerators:

- covering a very large range of temperature levels (particularly interesting for high temperature values),
- using low cost natural materials (rock) or efficient ceramics.

Current R&D status:

- An experimental device (*CLAIRE*) has been built and tested with air as heat transfer fluid:
  - two test sections volumes (1.2 x 1.2 x 5 m) working at temperatures between 600 and 1300 °C
  - Tests have been made with gravels and structured ceramics at 800°C
  - Dynamic thermo-aeraulics models have been developed for sizing purposes.
  - Three dimensional CFD simulations have been validated on experimental results.

Further information:

- Contacts: jean-francois.fourmigue@cea.fr and pierre.garcia@cea.fr
- Desrues, T., Ruer, J., Marty, P., Fourmigué, J.F. A thermal energy storage process for large scale electric applications (2010). Applied Thermal Engineering, 30 (5), pp. 425-432
- Reboussin, Y., Fourmigué, J.F., Marty, Ph., Citti, O. A numerical approach for the study of glass furnace regenerators (2005). Applied Thermal Engineering, 25 (14-15), pp. 2299-2320.
- Esence, T., Bruch, A., Molina, S., Stuttz, B., Fourmigué, J.F., A review on experience feedback and numerical modeling of packed-bed thermal energy storage systems, Solar Energy 153 (2017) 628–654.

Future work:

- Validation of simulations, dynamic 1D models or CFD, has to be improved.
- A 250 kWh demonstration unit has been built and connected to the AlsolenSup demonstrator, it will be tested in the next months.
  - Temperature range from 300 to 450 °C
  - Horizontal brick regenerator powered by reversible fans,
  - Integrated in a CSP Fresnel power plant demonstrator.

CEA – LITEN (France)

FROM RESEARCH TO INDUSTRY

SolarPACES

TASK III-TES

Heat storage with dual media thermocline

Challenges:

- NREL at Solar Paces 2010: "Thermocline is uncontrollable and unpredictable", making such system inefficient and unusable;
- Very limited experimental data available in the literature and few dual media thermocline installations built up to now. In addition, most of the experimental data show scattering and was obtained in limited range of operating parameters;
- Construction of a dual media thermocline at commercial CSP plant size. Up to now, only one industrial dual-media thermocline has been built (Solar One solar tower);
- Interaction between storage material and thermal fluid.

State of the art:

- Thermocline with spheres-bed or rock-bed using air as heat transfer fluid → no fluid/solid interaction;
- No systematic study of the influence of operating parameters and control strategy.

Concept approach:

Low cost and robust heat storage dual media thermocline characterized by:

- non pressurized thermal oil as thermal fluid;
- no expansive natural rock as storage material;
- additional porosity reduction by using multiple rock sizes;
- possible oil/rock interaction leading to rock and/or oil degradation.

Current R&D status:

- A prototype-scale (*STONE* ≈ 3 m3) thermocline is successfully operated
  - Highly controllable and predictable operation,
  - Tests campaigns allow to finely understand the hydraulic and thermal behaviors in controlled operating conditions,
- A demonstrator-scale (≈ 30 m3) thermocline is successfully operated
  - Integrated in a CSP Fresnel power plant prototype,
  - Allows to validate the behavior, the control and the performances of a dual thermocline storage unit in real operating conditions.
- Our numerical model shows good agreement with the experimental data and can be used for thermocline size extrapolation with good confidence level, for performance predictions and for the definition of operating strategies of commercial CSP plants.

Further information:

- Contact person: arnaud.bruch@cea.fr
- Bruch, A., Fourmigue, J.F., Couturier, R., Molina S., Experimental and numerical investigation of stability of packed bed thermal energy storage for CSP power plant, Energy Procedia 49 (2014) 743 751.
- Bruch, A., Fourmigue, J.F., Couturier, R., Experimental and numerical investigation of a pilot-scale thermal oil packed bed thermal storage system for CSP power plant, Solar Energy 105 (2014) 116–125.
- Esence, T., Bayón, R., Bruch, A., Rojas, E., Study of thermocline development inside a dual-media storage tank at the beginning of dynamic processes, AIP Conference Proceedings, 1850, 080009 (2017).
- Bruch, A., Molina, S., Esence, T., Fourmigué, J.F., Couturier, R., Experimental investigation of cycling behaviour of pilot-scale thermal oil packed-bed thermal storage system. Renewable Energy 103, 277-285 (2017).

Future work:

- Optimization of thermocline control strategy for efficient integration in a CSP power plant.
- Test of different storage material and filling procedures.

CENER (Spain)

CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES
ADItech

SolarPACES
TASK III-TES

Transient simulation of TES systems

Challenges:

Due to the fluctuating nature of solar energy, solar thermal power plants often operate under transient conditions. Thus, whenever TES is applied in these plants, also the storage system is subjected to transients. In many cases, the thermal inertia of the TES system limits the operation strategy of the whole plant, e.g. so that a short cloud pass cannot be balanced by the storage system, since it would take too long to switch from charging to discharging operation. Hence, when optimizing operation strategies the transient response of the TES system must be known.

State of the art:

So far, most modelling procedures focus on quasi-steady models where transient responses cannot be reproduced.

Concept approach:

At the Solar Thermal Energy Department at CENER a very flexible Modelica model library is being developed, which allows the detailed transient analysis of single plant components as well as of the whole solar thermal power plant on system level. This allows the simulation of operating strategies and control loops that are very close to reality.

Current R&D status:

Currently, the library includes detailed TES models of:

- the conventional active-indirect two-tank type,
- the conventional active direct two-tank type,
- packed-bed thermocline type,
- as well as passive sensible and latent TES type.

Furthermore, these models can be simulated in a full power plant model on system level.

Further information:

- Contact person: Dr. Fritz Zaversky (fzaversky@cener.com)
- F. Zaversky, Object-oriented modeling for the transient performance simulation of solar thermal power plants using parabolic trough collectors - A review and proposal of modeling approaches for thermal energy storage, PhD Thesis, Public University of Navarre, Pamplona, Spain, 2014 (http://academica-.unavarra.es/handle/2454/16705)
- F. Zaversky, M. Sánchez, D. Astrain, Object-oriented modeling for the transient response simulation of multi-pass shell-and-tube heat exchangers as applied in active indirect thermal energy storage systems for concentrated solar power, Energy, 65 (2014) 647-664
- I. Hernández Arriaga, F. Zaversky, D. Astrain, Object-oriented Modeling of Molten-salt-based Thermocline Thermal Energy Storage for the Transient Performance Simulation of Solar Thermal Power Plants, Energy Procedia, 69 (2015) 879-890

Future work:

Application of the developed models to improve and optimize operation strategies.

CIEMAT-PSA (Spain)

TASK III-TES

Simulation of thermocline tanks

Challenges:

- Describe thermocline tank behavior by means of an analytical function that provides outlet temperature with time so that it can be easily implemented in the annual simulations of a CSP plant

State of the art:

- Thermocline tank behavior mainly described by numerical models: 1D, 2D, 3D, CFD calculations models.
- Only some examples of analytical models are found in the literature
- Not many experimental results for thermocline tanks meant to be used in CSP plants
- Validation of the models still required

Concept approach:

- Thermocline tank performance should be described by a simple but accurate enough model
- Single-phase one dimensional model: effective storage medium formed by either a liquid or both a liquid and a solid filler.
- First stage: numerical model
- Second stage: analytical model
- Third stage: CSP plant implementation

Current R&D status:

- Improvement of the model previously developed by using experimental data from thermocline tanks with/without solid filler
- Analytical model based on sigmoid functions
- Correlation between function parameters, tank parameters and operating conditions

Further information:

Contact person: Rocío Bayón; rocio.bayon@ciemat.es

- Esence T., Bayón R., Bruch A., Rojas E. Study of Thermocline Development Inside a Dual-media Storage Tank at the Beginning of Dynamic Processes, AIP Conference Proceedings, 1850, 080009 (2017).
- Bayón R., Rojas E.: Analytical function describing the behavior of a thermocline storage tank: a requirement for annual simulations of solar thermal power plants. International Journal of Heat and Mass Transfer 68 (2014) 641-648.
- Bayón R., Rojas E.: Simulation of thermocline storage for solar thermal power plants: From dimensionless results to prototypes and real-size tanks. International Journal of Heat and Mass Transfer 60 (2013) 713-721.
- Bayón R., Rivas E., Rojas E.: Study of thermocline tank performance in dynamic processes and stand-by periods with an analytical function, SolarPACES 2013. Las Vegas (USA), September 2013. Oral presentation.
- Bayón R., Rojas E., Rivas E.: Effect of storage medium properties in the performance of thermocline tanks, SolarPACES 2012. Marrakech (Morocco), September 2012. Poster.

Future work:

- Defining more accurately thermocline transient behavior at the beginning of dynamic processes after total or partial thermocline extraction.
- Validation with experimental data from thermocline tanks with/without filler.

CIEMAT-PSA (Spain)

TASK III-TES

Simulation of CSP plants with single tank storage

Challenges:

- Develop flexible models for the simulation of CSP plants, including different configurations and technologies for the solar field and using different working fluids and storage systems.
- Perform annual production estimations using the simulation models.
- Analyze the integration of TES in CSP plants under different strategies for plant operation with storage systems.

State of the art:

- Wide variety of simulation models for CSP plants with conventional working fluids and two-tank TES systems.
- Few examples of thermocline TES systems integrated in CSP plant models. Low accuracy and flexibility.
- Operation strategies of TES systems in CSP plants not analyzed in the literature.

Concept approach:

- Develop a simulation model of parabolic-trough CSP plant in TRNSYS software, including the solar field, the storage system and the power block and several working fluids (oil, molten salts).
- Adapt and implement the analytical function for the thermocline behavior in TRNSYS suitable to be integrated into the CSP plant model.
- Define possible operation strategies for parabolic-trough CSP plants using either two-tank or thermocline TES systems. Implement them in the CSP plant model.
- Run the simulations for typical meteorological data and compare the annual results.

Current R&D status:

- Model for CSP plants with parabolic troughs with HTF oil or molten salts
- Thermal storage in two-tank or thermocline configuration
- Analysis of operation strategies for the storage system and their effect on the annual production and the auxiliary consumption of fossil fuel.

Further information:

Contact person: Rocío Bayón; rocio.bayon@ciemat.es and Mario Biencinto; mario.biencinto@ciemat.es

- Biencinto M., González L., Valenzuela L., Fernández A.: Design and Simulation of a Solar Field Coupled to a Cork Boiling Plant. Solar Heating and Cooling Conference, Freiburg (Germany), September 2013. Poster.
- Biencinto M., Bayón R., Rojas E., González L: Simulation and assessment of operation strategies for solar thermal power plants with thermocline storage tank. Solar Energy 103 (2014) 456-472.
- Biencinto M., González L., Zarza E., Díez L.E., Muñoz-Antón, J.: Performance model and annual yield comparison of parabolic-trough solar thermal power plants with either nitrogen or synthetic oil as heat transfer fluid. Energy Conversion and Management 87 (2014) 238-249.

Future work:

- Validation with more experimental data
- Simulation of other plant technologies such as CR or DSG plants
- Economic and feasibility study of CSP plants with new TES concepts

CIEMAT-PSA (Spain)

TASK III-TES

Molten Salt Test Loop for Thermal Energy Storage (MOSA)

Challenges:

- Reliability of components used in molten salt loops under CSP conditions
- Optimization of different operation procedures for CSP storage systems based on molten salts

State of the art:

- This test loop is a replica of a two-tank thermal storage system with molten salts

Description:

- Vertical hot tank and horizontal cold tank with 40t of molten salt inventory
- A thermal oil loop that can be used for either salt heating up to 380°C or cooling down to 290°C.
- A CO_2/molten salt heat exchanger for salt heating up to 500°C with CO_2 supplied by parabolic trough collectors
- Two flanged sections where different components for this type of loops (e.g. valves, flow meters, heat trace, pumps…) can be tested
- Being a down-scaled facility of a commercial two-tank molten salt storage system everything related to this type of systems can be tested in a more simple way

Applications:

- Test of different components (pumps, valves, flowmeters, etc.) for their use in a molten salt medium
- Optimization of operation procedures under both normal and risky situations for a two-tank system configuration
- Designing recovery procedures
- Validation of models and simulation approaches for molten salt storage systems
- Characterization of both molten salt/oil and molten salt/gas heat exchangers
- Characterization of thermocline tanks.

Further information:

Contact person: Margarita Rodríguez; margarita.rodriguez@psa.es

- M. M. Rodríguez-García, E. Zarza, "Design and Construction of an Experimental Molten Salt Test Loop", 17th International SolarPACES Conference, Granada (Spain), September 2011.
- M.M. Rodríguez-García, M. Herrador Moreno, E. Zarza Moya, Lessons learnt during the design, construction and start-up phases of a molten salt testing facility, Applied Thermal Engineering, Vol. 62, Issue 2, Pages 520-528, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2013.09.040.
- J. Bonilla, M.M. Rodríguez-García, L. Roca, L. Valenzuela, Object oriented modeling of a multi-pass shell-and-tube heat exchanger and its application to performance evaluation, IFAC-Papers online, Vol. 48, Issue 11, 2015, Pag. 97-102, ISSN 1876-6102, http://doi:10.1016/j.ifacol.2015.09.166
- L. Roca, J. Bonilla, M.M. Rodríguez-García, P. Palenzuela, A. de la Calle, L. Valenzuela, Control strategies in a thermal oil-molten salt heat exchanger, AIP Conference proceedings 1734, 130017 (2016), http://doi:10.1063/1.4949227

CIEMAT-PSA (Spain)

TASK III-TES

Test benches with molten salts (BES-I & BES-II)

Challenges:

- Validation and testing of components used in molten salt installations.

State of the art:

- These loops are intended for performing validation test for conventional components used in molten salt circuits in a simple and quick way

Description:

- Two test benches, BES-I and BES-II, are especially designed for testing of valves, pressure transmitters and other molten salts components under real working conditions up to 600ºC and 40 bar. Components with nominal diameters from 2” up to 6” can be evaluated in these test benches.

Applications:

- Tests for different types of valves
  1. Leakage test
  2. Validity for design conditions test
  3. Cold zone test
  4. Packing life test
- Tests for pressure transmitters
  1. Constant pressure test
  2. Pressure variation test
- Validation of other components and auxiliary equipment like heat tracing, insulation, etc.

Further information:

Contact person: Margarita Rodríguez; margarita.rodriguez@psa.es

- M-M. Rodriguez-Garcia, E. Rojas, M. Pérez, Procedures for testing valves and pressure transducers with molten salt, Applied Thermal Engineering, Volume 101, 25 May 2016, Pages 139-146, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2016.02.138.
- M.M. Rodríguez-García, A. López-Tamayo, E. Rojas, Components test device with molten salt at high temperature and pressure. 20th International SolarPACES Conference, Beijing (China), September 2014.

DLR: German Aerospace Center (Germany)

DLR

SolarPACES

TASK III-TES

MOLTEN SALT STORAGE

Challenges:

The two-tank molten salt storage is commercially available. However, cost reduction and higher operation temperature ranges are required for a wider application field. The challenges are:

- Development of alternative salt systems
  - Lower melting temperature
  - Stability at higher temperatures
- Cost reduction – alternative tank design/materials/components
- Components and materials for higher temperatures

State of the art:

See above

Concept approach:

- Research on new salt mixtures
- Alternative tank design (e.g. Thermocline – single tank with filler material)

Current R&D status:

- New salt mixtures
- Stability tests for Solar Salt
- Design and call for tenders of a molten salt test facility
  - 60 m^3 Molten Salt (e.g., 60 wt.% NaNO3 and 40 wt.% KNO3)
  - Temperature range 250 to 560 °C
  - Mass flow rate up to 8 kg/s

Further information:

- Contact: Thomas Bauer; thomas.bauer@dlr.de
- **Bauer, T., Pfleger, N., Laing, D., et al**. (2013) Chapter 20: High temperature molten salts for solar power application, *in* "Molten Salt Chemistry: from Lab to Applications, " *edited by* Lantelme, F. and Groult, H., Elsevier.
- **Bauer, T., Steinmann, W.-D., Laing, D., et al**. (2012) Chapter 5: Thermal energy storage materials and systems, *in* "Annual Review of Heat Transfer, Vol. 15, " *edited by* Chen, G., Begell House, Inc., *pp.* 131-177, doi: 10.1615/AnnualRevHeatTransfer.2012004651.

Future work:

- Further research on new salt mixtures
- Stability tests of salt mixtures under different atmospheres
- Commissioning of molten salt test facility “TESIS” in 2017
- Comparison of tank concepts
- Analysis of filler materials
- Testing of components
- Analysis of operational molten salt aspects

ENEA (Italy)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

SolarPACES

TASK III-TES

Innovative concept of a thermal energy storage system based on a single tank configuration using stratifying molten salts

Challenges:

- Assessment of a TES-SG (Thermal Energy Storage- (integrated) Steam Generator) system based on a single tank containing a thermal storage liquid material (HSM: heat storage material)
- Store energy (during the charging phase) as sensible heat, and, during thermal discharging, transfer the energy to another fluid by a heat exchanger immersed into the HSM bulk.
- Maintain a vertical thermal stratification profile in the HSM fluid (thermocline), due to the layers difference of density with temperature

State of the art:

- Two tanks based systems (a hot and a cold one) are currently employed as TES systems, in particular coupled with parabolic trough solar (PCS) plants
- ENEA (along with Ansaldo) developed an international patent about the possibility to employ a more compact integrated TES system consisting of a unique storage tank and an immersed SG.

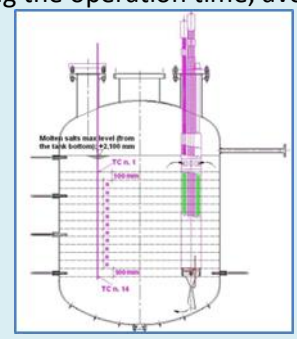
Concept approach:

Thermal energy storage system based on a single tank with an integrated heat exchanger:

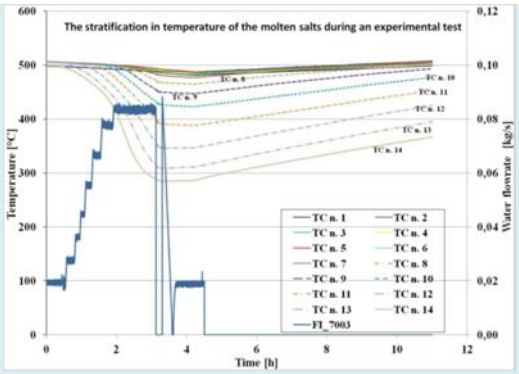
- lower costs for heat storage
- higher possibilities for TES systems modularity
- lower cost for the steam generator

Current R&D status:

- Several experimental results have been collected in the operation of the PCS facility located at the ENEA Casaccia centre
- Molten nitrate ($NaNO_3/KNO_3$ 60/40 wt%) stratification behaviour has been confirmed and investigated
- The experimental work has shown that the thermal stratification can be maintained quite constant for several hours and the presence of the integrated steam generator actively guarantees and maintains the stratification during the operation time, avoiding mixing of the stratified layers



Scheme of the experimental set-up



Trends of MS temperatures and water flow rate during an experimental test

Further information:

- Contact person: Ing. Walter Gaggioli , ENEA UTRINN/STD, walter.gaggioli@enea.it
- Associated funded project: OPTS (OPtimization of a Thermal energy Storage system with integrated Steam Generator), CP-FP7
- Gaggioli et. Al – "An innovative concept of a thermal energy storage system based on a single tank configuration using stratifying molten salts as both heat storage medium and heat transfer fluid, and with an integrated steam generator" – Solar Paces (2013) - Energy Procedia 00 (2013) 000–000

Future work:

- Optimization of charging/discharging cycles for the TES-SG system, and upgrading of the experimental apparatus equipment
- Study on tank and SG new feasible materials, with the aim of further decreasing thermal storage investment costs
- Modeling and experimental investigations about the possibility of using solid filler materials coupled with the molten nitrates, in order to decrease the HSM (heat storage materials) costs.

ENEA (Italy)

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

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TASK III-TES

Employment of low melting nitrate/nitrite mixtures as HTF and HSM

Challenges:

- Decrease the HTF (heat transfer fluid) initial solidification point, with the main target to improve management and maintenance operation of a solar plant
- Design of a more economical thermal energy storage system for plants where thermal oil is employed as HTF, and where the maximum operating temperature is around 400 °C
- Definition of the operational characteristics for the integration of these HTF/HSM in the currently used solar energy technology

State of the art:

- Nitrate/nitrite based low melting mixture has been widely investigated in the recent scientific literature. Some of these mixture compositions have been patented
- For some of these mixtures the value of the maximum allowed operating temperature is not clearly established
- A few ternary/quaternary phase diagrams are already present in the scientific literature and some thermodynamics models are proposed.

Concept approach:

- Employment of low melting materials as HTF/HSM (<100-140 °C of initial solidification temperature) as an alternative to an alkaline nitrate mixture where a lower maximum temperature is to be used
- Possible less costly alternative for thermal oils
- Possibility to decrease the thermal storage components material costs
- Less costly maintenance operations

Current R&D status:

- Validation of thermo-physical properties
- An experimental campaign to study thermal degradation properties is currently on-going, by using a properly designed experimental set-up
- Modeling activity

Further information:

- Contact person: Dr. Salvatore Sau, ENEA DTE STT ITES; salvatore.sau@enea.it
- Publications:
  - Sau, S., Corsaro, N., Crescenzi, T., D'Ottavi, C., Liberatore, R., Licoccia, S., Russo, V., Tarquini, P., Tizzoni, A.C.Techno-economic comparison between CSP plants presenting two different heat transfer fluids(2016) Applied Energy, 168, pp. 96-109
  - Tizzoni, A.C., Sau, S., Corsaro, N., Giaconia, A., D'Ottavi, C., Licoccia, S. Thermal fluids for CSP systems: Alkaline nitrates/nitrites thermodynamics modelling method (2016) AIP Conference Proceedings, 1734
- Associated Funded Project:
- Accordo di Programma Ministero dello Sviluppo Economico – ENEA sulla Ricerca di Sistema Elettrico, Progetto B.1.3, Energia da fonte Solare, Linea Progettuale 2: Solare termodinamico, Studio di configurazioni impiantistiche alternative;
  Accordo di Programma Ministero dello Sviluppo Economico - ENEA
  Piano Annuale di Realizzazione 2015
  Area: Generazione di Energia Elettrica con Basse Emissioni di Carbonio
- Progetto: B.1.1 Bioenergia
  Obiettivo: Tecnologie per la produzione diretta di energia elettrica attraverso la combustione di biomasse;
- SFERA II (Solar Facilities for the European Research Area II);
- STAGE-STE (Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy)

Future work:

- Completion of thermal stability analysis
- Compatibility study between low melting mixtures and (possibly economical) materials feasible to be used for the construction of thermal storage components (tank, SG)
- Simulation thermodynamic models with the aim to develop predictive tools for new low melting mixtures
- It is necessary to complete the knowledge about ternary/multicomponent phase diagrams. The thermodynamics models proposed in the scientific literature are to be applied, validated and, where necessary, improved

ENEA (Italy)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

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TASK III-TES

Thermal Energy Storage with ceramic material

Challenges:

- Thermal energy storage at high temperature (about 560 °C) and high pressure (about 100 bar), for solar power plant with dry air as heat transfer fluid
- Design of a thermal energy storage element at high pressure and temperature
- Definition of the operational characteristics for the integration of the storage system into the solar plant

State of the art:

- Preliminary mechanical design of the thermal storage element
- Development of a software tool for simulating the solar heat charge and discharge

Concept approach:

- Simple design, for a high operational reliability of the storage system
- High heat transfer surface per unit mass of storage material

Current R&D status:

- Thermo-hydraulic software developed for simulating the solar field in operation
- Thermo-hydraulic software currently under development, for simulating the thermal energy storage in operation

Further information:

- Contact person: Antonio De Luca, ENEA DTE-STT; antonio.deluca@enea.it
- Associated Funded Project: Accordo di Programma Ministero dello Sviluppo Economico – ENEA sulla Ricerca di Sistema Elettrico, Progetto B.1.3, Energia da fonte Solare, Linea Progettuale 2: Solare Termodinamico, Studio di configurazioni impiantistiche alternative:A. De Luca: Valutazione dell'utilizzo di fluidi gassosi in impianti solari termodinamici (2013)

Future work:

- A prototype of the storage element should be realized and tested, for measuring the characteristic parameters to be compared with the results of the software developed for controlling the storage system in operation

Fraunhofer ISE (Germany)

Fraunhofer ISE

SolarPACES TASK III-TES

Thermal storage in a single thermocline tank

Challenges:

- Single-tank molten salt storage concepts promise cost reduction compared to the state-of-the-art two-tank storage system but may have lower efficiency due to mixing processes
- Lack of experimental data for single-tank systems to assess the actual performance prevent the commercial application of single-tank storage systems

State of the art:

- Two-tank storage system where cold and hot fluid are separated in individual tanks
- Single-tank storage is only available for hot water

Concept approach:

- Design, construction and testing of a molten salt single-tank prototype
- Parameter identification for numerical models to improve the accuracy of simulations
- Small test facility allows for versatile operating conditions (flow rate and heat loss) but area to volume ratio is worse than for large-scale tank

Current R&D status:

- Initial testing and characterization of the system

Further information:

- Contact: Tom Fluri (tom.fluri@ise.fraunhofer.de)
- B. Seubert, R. Müller, D. Willert, T. Fluri: Experimental results from Laboratory-Scale Molten Salt Thermocline Storage. SolarPaces, Abu Dhabi, 2016.

Future work:

- Identifying the impact of boundary conditions such as molten salt flow rate and temperature difference as well as heat loss and standby performance

Fraunhofer ISE (Germany)

Fraunhofer ISE

SolarPACES TASK III-TES

Thermocline Tank Simulation

Challenges:

- Single-tank molten salt storage concepts promise cost reduction compared to the state-of-the-art two-tank storage system but may have lower efficiency due to mixing processes
- Modelling of the mixing processes is either neglected in simple 1D-models or tremendous effort in CFD simulations

State of the art:

- 1D models with first-order methods for the convective fluxes introduce numerical diffusion which can be interpreted as mixing but is only a numerical effect
- Mixing is not a function of the charging velocity or temperature difference
- System integration of alternative storage concepts is often neglected

Concept approach:

- Development of a storage model with higher-order schemes which is not susceptible to numerical effects but still allows for fast simulations
- Implementation of a mixing factor that considers inlet flow rate and temperature difference
- Integration of the model into the system simulation program ColSim CSP to perform annual simulations and evaluate storage performance in system context for e.g. the ORC-PLUS project

Current R&D status:

- Alternative algorithms for the implementation of mixing
- Integration of the option to insert filler materials into storage

Further information:

- Contact: Tom Fluri (tom.fluri@ise.fraunhofer.de)
- B. Seubert, T. Fluri and W. Platzer: Numerical investigation of a high temperature stratified storage with integrated steam generator. SolarPaces, Las Vegas, 2013.

Future work:

- Performing parameter identification studies to match numerical models to mixing analyzed in experimental data
- Intensify evaluation and characterization of thermocline storage

IEE-CAS (China)

TASK III-TES

Molten Salt Thermocline Thermal Storage Technology

Challenges:

- Traditional two tank molten salt thermal storage system need huge tons molten salt and very big storage tank which increase the cost of the CSP power plant.
- Single tank thermocline thermal storage system could greatly decrease the cost but there are not commercialized MS thermocline thermal storage system in real power plant.

State of the art:

- There a lot of parameters which influence the stability of thermocline thickness are still not systematically studied.
- How the unsteady inlet conditions and multicycle influence the thermocline are still well studied.
- A general dimensionless relation which could reflect the mechanism of thermocline is needed.

Concept approach:

- Mechanism research:
  - The influence of physical parameters on the thermocline system.
  - The influence of physical boundary conditions on the thermocline system.
  - Advantages:
    - It is better to find the methods to improve the performance of the thermocline thermal storage system.
- Dynamic simulation for single and two tank combined thermal storage system:
  - Advantages: The new designed combined thermal storage system will have more stable thermocline and lower cost.

Current R&D status:

- The influence of parameters and physical boundary conditions have been finished numerical simulation

Further information:

- Contact person: changzheshao@mail.iee.ac.cn
- ZS Chang, X Li, C Xu, C Chang, ZF Wang. The design and numerical study of a 2MWh molten salt thermocline tank. Energy Procedia. 2015,69:779~789. SolarPACES 2014, September 16-19, 2014 in Beijing, China

Future work:

Continue all the work. The PhD student will go on the work in PROMES, France as visiting student.

IEE-CAS (China)

SolarPACES

TASK III-TES

Two Tank Storage Using Molten Salt

Challenges:

- Narrow work temperature range of molten salt, especially the high freezing point=> extend the safe work temperature range, keep tube temperature by using electric heat tracing and change ratio of salt mixture.
- Large tank and abundant salt needed.
- Flexible control strategy of molten salt system => suitable control strategy.

State of the art:

The main and typical way of thermal storage in CSP power plants.

Concept approach:

- Extend the safe work temperature range:
  - Advantages: make full use of thermal potential.
  - Disadvantages: raise disk of accident.
- Change ratio of salt mixture:
  - Advantages: find low freezing point salt mixture.
  - Disadvantages: expensive.
- Suitable control strategy:
  - Set various system operation modes and use corresponding control methods when system runs.
  - Advantage: raise the whole thermal storage and efficiency.
  - Disadvantages: bad switch and salt left in specific tubes between modes changing.

Current R&D status:

- Suitable control strategy is under way.

Further information:

- Contact person: lizhi@mail.iee.ac.cn

Future work:

- Build test facilities to do thermal storage experiments and optimize control strategy.

IEE-CAS (China)

SolarPACES

TASK III-TES

Two tanks TES using thermal oil

Challenges:

- High freezing point=>keep tank and tube temperature using electric heat tracing in winter.
- Low operation temperature=>using two stages TES to produce superheated steam to generate.

State of the art:

The main and typical way of thermal storage in CSP power plants

Concept approach:

- Decrease freezing point:
  - Advantages: the system can be operation in winter without using electric heat.
  - Disadvantages: TES cost is higher.
- Two-stage TES:
  - TES composited thermal oil TES and steam TES which thermal oil as the high temperature TES and steam as the low temperature TES.
  - Advantage: improve TES efficiency.
  - Disadvantages: control strategy is not easy.

Current R&D status:

Two stages TES is the TES of 1MW CSP plant of Badaling CSP in Beijing, China.
Many experimental had finished.

Further information:

Contact person: wangyan955@126.com

Future work:

- Continue the simulation and experiment of two stages TES.
- Improve the storage performance and establish evaluation criterion of thermal oil thermal storage.

IEE-CAS (China)

TASK III-TES

Solid packed bed thermal storage using high temperature air

Challenges:

- High cost of thermal storage with two tanks=>single thermal storage tank of solid material and/or liquid material
- Melting point temperature limitations of nitrate salts and thermal oil =>high temperature air and solid thermal storage material
- Low conductivity solid sensible thermal storage material=>composite sensible and latent material as thermal storage material
- Operation characteristic of packed bed thermal storage

State of the art:

Up to now, there is little attention of the control strategy and evaluation criterion of solid thermal storage performance using air as heat transfer fluid.

Concept approach:

- Composite sensible and latent material as thermal storage material
- Advantages:
  - The outlet temperature of discharging process is stability.
  - Improve convection and conduction between air and thermal storage
- Requirements:
  - Encapsulating the sensible and latent materials
  - Expand the thermocline area
  - Low cost

Current R&D status:

- The heat transfer performance of packed bed thermal storage was investigated by experiment and simulation
- The 500kWh$_{th}$ experimental test platform has finished
- Collaboration with other institution for solid thermal storage material

Further information:

- **Contact person:** wangyan955@126.com
- Yan Wang, Fengwu Bai, Zhifeng Wang. Experimental research of the heat transfer characteristics using a packed-bed of honeycomb ceramic for high temperature thermal storage system. Energy Procedia, 2015, 69:1059 ~1067.
- Yan Wang*, Bei Yang, Fengwu Bai. Heat Transfer Performance Research of Honeycomb Ceramic Thermal Energy Storage. Solar World Congress, Korea, November , 2015,

Future work:

- Continue the simulation and experiment of solid packed bed thermal storage system
- Improve the storage performance and establish evaluation criterion of solid thermal storage

IEE-CAS (China)

TASK III-TES

Solid Sensible Thermal Storage Using Concrete

Challenges:

- Low utilization of the storage material => extend the work temperature range and propose new control strategy
- Fluid outlet temperature increase during charging process, the concrete storage system and solar field will form a vicious circle when storage system integrate in CSP power plant => new control strategy
- Fluid outlet temperature decrease during discharging process => optimization design for concrete storage system

State of the art:

Up to now, little attention for storage material utilization and storage performance when integrate concrete system in CSP power plants.

Concept approach:

- Optimization design:
  - Unit storage cost as objective function, fluid outlet temperature and discharge power as constraints
  - Advantages:
    - Both storage cost and storage performance were considered
    - Design parameters could be given directly by using mathematical method
- New control strategy:
  - Modular control strategy: increase/decrease the concrete temperature at the end of charging/discharging process
  - Preheat solar field and power block with concrete storage: decrease the storage temperature before charging process
  - Limitation of charging mass flow for storage system: increase the charging time
  - Advantage: utilization of storage material and solar field were improved

Current R&D status:

- optimization design method have been finished
- simulation including solar field, storage system and power block using new control strategy is under going

Further information:

- **Contact person:** jianyongfang@mail.iee.ac.cn
- Y. Jian, Q. Falcoz, P. Neveu, F. Bai, Y. Wang, Z. Wang, Design and optimization of solid thermal energy storage modules for solar thermal power plant applications, Applied Energy, 139 (2015) 30-42.
- Y. Jian, F. Bai, Q. Falcoz, Z. Wang, Control Strategy of the Module Concrete Thermal Energy Storage for Parabolic Trough Power Plants, Energy Procedia, 69 (2015) 891-899.

Future work:

- Continue the simulation using new control strategy, and combined latent and sensible heat storage will be considered in the future

IEE-CAS (China)

TASK III-TES

Honeycomb ceramics used as storage media for CSP system using gas as heat transfer fluid

Challenges:

- High working pressure drop => optimization of the system design and operation
- Fluid outlet temperature decrease during discharging process => optimization design

State of the art:

Up to now, no operating system in CSP power plants.

Concept approach:

- Thermal performance experiments
  - Advantages:
    - Easy to get the performance of whole working process.
  - Disadvantages:
    - Not easy to get the optimization design.

Current R&D status:

- Some experiments had finished.

Further information:

- **Contact person:** baifw@mail.iee.ac.cn

Future work:

- Finish the experiments and give the final evaluation of this technology.
- Do some simulations for the whole system and present the method of optimization of system design and operation.

IK4-TEKNIKER (Spain)

IK4 TEKNIKER Research Alliance

SolarPACES

TASK III-TES

Molten Salts (MS) for TES

Challenges:

- Condition monitoring of thermal and physical properties of these materials at working conditions
- Assessment of MS quality at different used stage
- Definition of operational limits for MS
- Synthesis of new MS with low melting temperature
- Find a compromise between low melting temperature Tm and corrosion properties of new MS

State of the art:

- There is not enough knowledge about the real service life of MS that operates in SCP plants

Concept approach:

Advanced test bench (up to 5kg) that can operate at real working conditions (P,T) with on line sensors to monitor chemical changes in the MS during ageing process

- Advantages:
  - New proposed materials for thermal storage application can be study/evaluated and characterize (thermal, physical and chemical properties)
  - Corrosion properties of constructive materials can be tested against thermal storage materials
    - New or current materials against new molten salts
    - New or current materials against current solar salts

Current R&D status:

- Advanced chromatographic techniques to evaluate MS composition
- Collaboration with other corporations to set up protocols for thermal characterization

Further information:

Contact person:

Nerea Uranga; nerea.uranga@tekniker.es and Cristobal Villasante; cristobal.villasante@tekniker.es

Future work:

Continue the study of new thermal materials for TES

IK4-TEKNIKER (Spain)

IK4 TEKNIKER Research Alliance

SolarPACES

TASK III-TES

ADVANCED Heat Transfer Fluids (HTF)

Challenges:

- Enhance thermal properties (Cp, thermal storage)
- Wide working temperature window of current HTF
- Reduce HTF volume in the installation
- Define operational limits of HTF in use
- Condition monitoring of HTF through advanced analytical techniques

State of the art:

- Current HTF has a solidification temperature of 12ºC and upper operational temperature at 398ºC, with limited thermal storage properties.
- Quality assessment is based on very basic techniques (real aged state of HTF is not known)

Concept approach:

- Selective HTF additivation with thermal active additives
  - Microencapsulated thermal material (Phase Change Material, Ionic liquids, Salts)
  - Non-encapsulated thermal materials
- Advance test-bench to evaluate new or current HTF behavior under simulated working conditions (T, P)
- Advanced techniques based on chromatography to assess and quantify degradation. (Selective identification and monitoring of chemical compounds)

Current R&D status:

- Collaboration with HTF manufacturers
- HTF with IL has higher thermal resistance without change pumpeability properties

Further information:

Contact person:

Marta Hernaiz; marta.hernaiz@tekniker.es and Cristobal Villasante; Cristobal.villasante@tekniker.es

- M.Hernaiz, N. Uranga Improved thermal fluids WO 2013182713 A1
- M. Hernaiz, E.Aranzabe LUBMAT 2012: “Condition monitoring of heat transfer fluid in parabolic trough collectors of solar power plants”
- M. Hernaiz SCP Today 2013-Strategies to improve solar heat transfer fluids behavior
- M. Hernaiz, N.Uranga LUBMAT 2012: “Improvement of solar heat transfer fluid behavior at low temperature by dispersing encapsulated and non encapsulated phase change materials (PCM)

Future work:

Continue in the research line of development “advanced HTF” with the aim of improve thermal properties

Masdar Institute (Emirates)

TASK III-TES

ACTIVITY: Concentrated Solar Power on Demand Demonstration project (CSPonD)

Challenges:

- Use of beam down technology
- Combination of TES system and volumetric receiver
- Single storage tank based on thermocline concept
- Demonstrate the technical and economic viability of the concept

State of the art:

Although there are only a few proposed concepts using one tank as TES system, this is the first time that it is combined with the receiver.

Concept approach:

Advantages:

- Reduction of parasitic loses inherent to commercial CSP plants
- Higher concentration Final Optical Element (FOE) because acceptance angle from CR is small compared to FOE for tower system
- Conical FOE. Improved spatial and angular distribution of flux at receiver aperture

Requirements

- An insulated divider is needed between hot and cold salts stored in the one tank TES system
- Use of commercially available components and materials

Current R&D status:

- Current prototype almost finished and being tested at Masdar Institute Solar Platform

Further information:

Contact person: Nicolas Calvet; ncalvet@masdar.ac.ae

- Concentrated solar power on demand, Alexander H. Slocum et al., Journal of Solar Energy, Volume 85, pp. 1519-1529, 2011
- Preliminary optical, thermal and structural design of a 100 kWth CSPonD beam-down on-sun demonstration plant, Benjamin Grange et al., Proceedings of the seventh international conference of applied energy, March 28-31, 2015, Abu Dhabi [UAE]

Future work:

- Improvement of FOE
- Improvement of divider plate
- Testing at industrial prototype scale

SUPSI, ETHZ ALACAES (Switzerland)

University of Applied Sciences and Arts of Southern Switzerland
SUPSI

SolarPACES

TASK III-TES

Numerical and experimental analysis of a packed bed TES system suitable for Adiabatic Compressed-Air Energy Storage (A-CAES) technology

Challenges:

- TES systems operating at high temperature (550°C) and high pressure (up to 100 bars).
- Experimental investigation on the pilot plant for demonstrating the applicability of A-CAES technology.

State of the art:

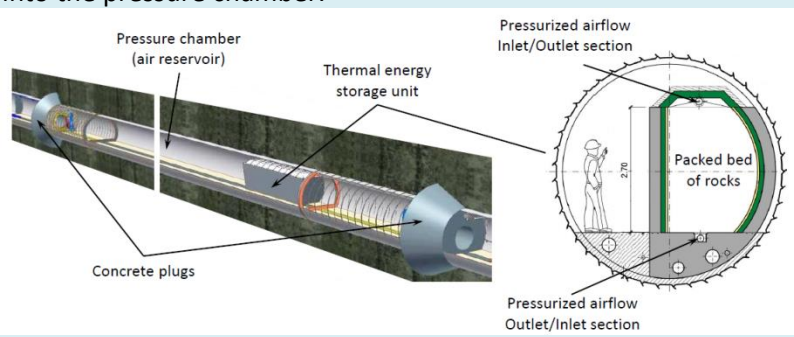
In the field of large-scale electric energy storage, a valid alternative to pumped hydroelectric energy storage is represented by compressed-air energy storage (CAES). As of today, two CAES plants are successfully in operation: the 321 MW Huntorf plant (Germany) and the 110 MW McIntosh plant (USA). The round-trip efficiency of these CAES plants, 42% and 54% for the former and the latter respectively, is limited by the fact that the thermal energy produced during compression is wasted and therefore they need to burn fuel to increase the enthalpy of the compressed air prior to expansion. To overcome the limitation of conventional CAES plants, the A-CAES concept of has been proposed. In this technology, a TES is exploited to store the thermal energy produced during compression to be recovered prior to expansion. The expected round-trip efficiency of A-CAES is in the order of 70%.

Concept approach:

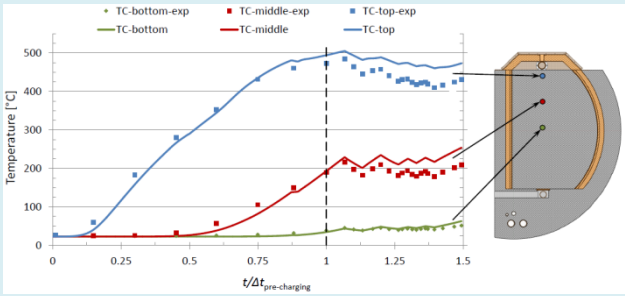
- Since the TES can be considered the key component of the A-CAES technology, its thermo-fluid dynamics behavior has been carefully evaluated by means of computational fluid dynamics (CFD) simulations.

Current R&D status:

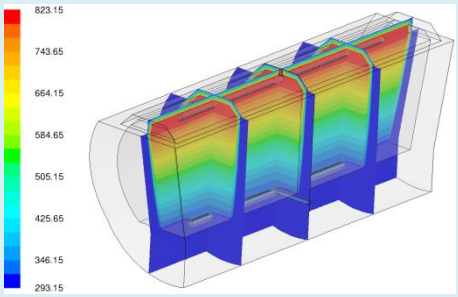
- To evaluate the feasibility and applicability of the AA-CAES concept, the first pilot plant has been built in Pollegio (CH). A 120 m long section of an existing tunnel in the Swiss Alps has been exploited as high-pressure air reservoir (up to 33 bars). The latter was enclosed by building two 5 m thick concrete plugs at the two ends. A single-tank TES, based on a 44 m^3 packed bed of natural rocks, has been installed into the pressure chamber.



- A 2D and 3D CFD modeling approach has been developed to evaluate the performance of the TES unit under investigation. The numerical model has been successfully validated with experimental data gathered from the Pollegio A-CAES pilot plant.



Numerical model validation: simulation results (solid lines) VS experimental data (markers)



TES unit temperature contours (Temperature [K])

Further information:

Contact person: Mr. Simone Zavattoni; simone.zavattoni@supsi.ch

- S.A. Zavattoni, L. Geissbühler, M.C. Barbato, G. Zanganeh, A. Haselbacher, A. Steinfeld, "CFD modeling of the Pollegio A-CAES pilot plant TES system", Swiss Competence Centre for Energy Research for Heat and Electricity Storage (SCCER-HaE), Annual report, 2016.

Future work:

Evaluating the effect of exploiting a combined sensible/latent heat TES solution.

SUPSI, ETHZ ALACAES (Switzerland)

University of Applied Sciences and Arts of Southern Switzerland

SUPSI

SolarPACES

TASK III-TES

Performance evaluation of the TES system integrated into the first pilot plant using air as heat transfer fluid

Challenges:

- Accurate description of the thermo-fluid dynamics behavior, and performance evaluation under cyclic conditions, of the packed bed TES unit integrated into the pilot plant.

State of the art:

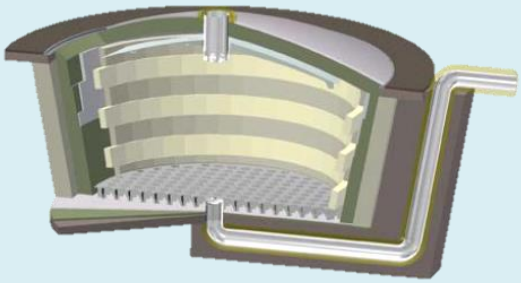
Single-tank, or thermocline, TES systems represent a reliable and affordable alternative to the commonly exploited two-tank solution in conventional CSP plants. Computational fluid dynamics (CFD) is a valuable tool for accurately analyzing the thermo-fluid dynamics behavior of this kind of TES allowing to predict the overall system performances.

Concept approach:

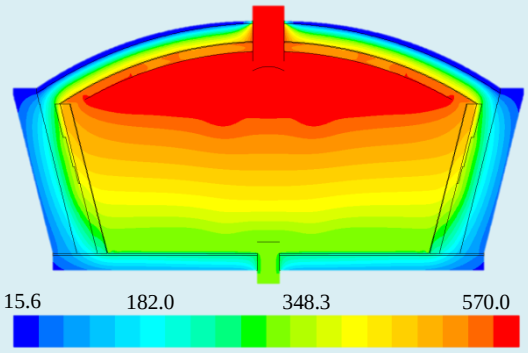
- A previously validated computational fluid dynamics (CFD) approach was followed to evaluate the thermo-fluid dynamics behavior of the TES unit under investigation subjected to a total of 5 pre-charging cycles followed by 60 consecutive cycles.
- The TES performance was also evaluated on the basis of the first- and the second-law of thermodynamics.

Current R&D status:

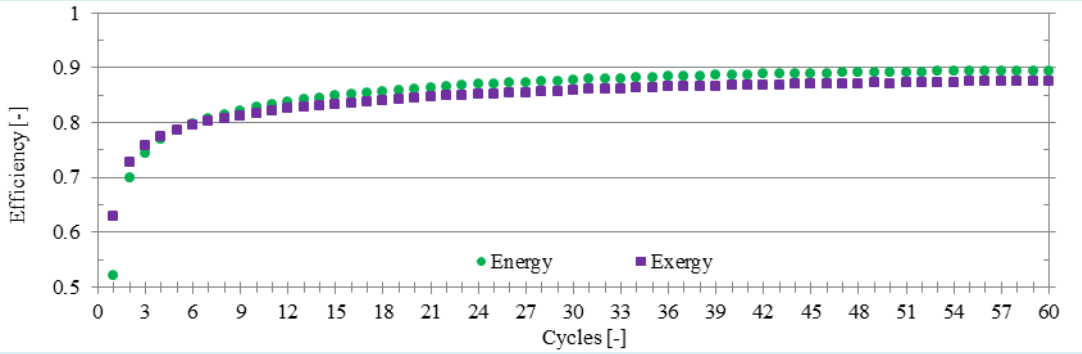
- The first 3 MW_{th} parabolic trough CSP pilot plant using air as heat transfer fluid has been constructed in Ait-Baha (Morocco).
- A packed bed TES unit, 100 MWh_{th} capacity, has been integrated into the pilot plant and accurately analyzed by means of transient CFD simulations:



CAD model of the TES unit



45th charging – Temperature contours (°C)



Resulting transient TES performance evaluation

Further information:

Contact person: Mr. Simone Zavattoni; simone.zavattoni@supsi.ch

- S. A. Zavattoni, G. Zanganeh, A. Pedretti, and M. C. Barbato, " Numerical analysis of the packed bed TES system integrated into the first parabolic trough CSP pilot-plant using air as heat transfer fluid," 23rd SolarPACES conference, 2017.
- S. A. Zavattoni, G. Zanganeh, A. Pedretti, and M. C. Barbato, "High temperature thermocline TES – Effect of system pre-charging on thermal stratification," AIP Conference Proceedings 1734 (050043), 2016.

Future work:

Evaluating the effect of some key parameters on thermal stratification.

TECNALIA (Spain)

TASK III-TES

Thermal Energy Storage (TES)

Challenges:

- Thermal Energy Storage solutions for very high temperature CSP: Novel salt mixtures, metallic and nano-enhanced HTFs, storage tank concepts and designs.
- Find a solution for thermal storage in DSG: research on metallic and nanosalt PCMs.
- Cost reduction of state of the art solutions, focused on TES and container materials.

State of the art:

Current TES systems are based on the double-tank concept. In spite their good performance and robustness, next generation CSP plants requires new materials and engineering concepts.

Concept approach:

TES FOR VERY HIGH TEMPERATURE CSP PLANTS.

- Advantage: other materials and concept solutions from other sectors where high temperatures are involved, such as space technology, can be transferred to CSP.
- Disadvantage: increased cost of materials and components. Gained efficiency needs to show a higher economic benefit than the extra cost.

TES FOR CSP PLANTS BASED ON DSG TECHNOLOGY. The research is focused on the development of PCMs and novel engineering structures to be used as PCM containers.

- Advantage: a higher amount of energy stored per unit of volume and, therefore lower costs per kWh will be achieved.
- Disadvantage: a balance must be reached between the higher cost of PCM materials and the savings derived from their application.

COST REDUCTION IN CURRENTLY USED SYSTEMS. Our interest is the research on novel nanostructured materials based on inorganic salts with enhanced heat transfer properties.

- Advantage: the amount of storage media is significantly reduced. This will have an impact on the global cost of the TES system.
- Disadvantage: further research is required to ensure the good performance and stability of these novel TES materials.

Current R&D status:

- Analysing other technologies for high temperature applications.
- Synthesis of low melting point metallic alloys and novel nanosalts as PCM for DSG.
- Optimization of heat transfer rate of current inorganic salts for double tank systems.

Further information:

- Contact person: Javier Nieto ; javier.nieto@tecnalia.com
- Muñoz-Sánchez B. et al. Assessment of the determination of Specific Heat of Molten Salt doped with Nanoparticles by means of the DSC Technique. Greenstock. Beijing 2015
- Muñoz-Sanchez B. et al. Nanoparticle Size Evaluation through Dynamic Light Scattering (DLS) technique in a Nitrate Salt doped with Ceramic Nanoparticles. CIIEM15. París (2015)
- Nieto-Maestre J. et al. Novel Metallic Alloys as Phase Change Materials for Heat Storage in Direct Steam Generation Applications. SolarPACES15. Cape Town (2015).

Future work:

- TES for very high temperatures: techno-economic analysis of considered concepts.
- TES for DSG: characterization of metallic and nanostructured PCMs. Compatibility with container materials and stability of physical and chemical properties.
- Sensible TES: more stable nanofluids based on salts with wider working temperature range

LATENT HEAT STORAGE

CEA – LITEN (France)

FROM RESEARCH TO INDUSTRY

SolarPACES

TASK III-TES

Latent Heat Storage with Phase Change Materials

Challenges:

- No available storage technology at commercial stage for DSG plants.
- Pure $NaNO_3$ is an attractive solution due to its favorable physical properties and low cost, but its low thermal conductivity impacts on the size and cost of the storage.
- The Latent Heat Storage module is the critical component for the storage system of a DSG solar plant; indeed it stores more than 50% of the total thermal energy.

State of the art:

- Graphite as heat transfer matrix below 250 °C.
- Encapsulated concept with metallic envelopes, not favorable for high pressure applications.
- Vertical bundle of parallel tubes with high pressure condensing/evaporating water inside and a static PCM volume outside.

Concept approach:

Low cost and robust heat transfer enhancement methods on the PCM side, for example using aluminum inserts around the vertical finned tubes:

- mass reduction of high pressure tubes,
- cost reduction of the heat exchanger,
- risk of corrosion due to $NaNO_3$.

Current R&D status:

- Small experimental loop with transparent test sections for visualization and phenomenological observation of low temperature PCM.
- Two PCM storage modules (3 m^3 and 1m^3) have been tested successfully on the *LHASSA* experimental facility:
  - Test campaigns to validate the thermo-hydraulic behavior of the storage under operating conditions similar to commercial DSG CSP plants,
  - Measured storage performances meeting the specifications,
  - Optimized operating procedures,
  - Good agreement with simulation results given by dynamic models developed at CEA,
- A demonstrator-scale (≈ 9 m^3) PCM storage was built and will be operated in the next months:
  - Integrated in a CSP Fresnel power plant prototype.

Further information:

- Contact person: Pierre Garcia ; pierre.garcia@cea.fr
- Longeon M., Soupart A., Fourmigué J.-F., Bruch A., Marty P., Experimental and numerical study of annular PCM storage in the presence of natural convection, Applied Energy, vol. 112, no. 0, pp. 175-184 (2013).
- Olcese M, Couturier R, Fourmigué JF, Garcia P, Raccurt O, Robin JF, Senechal B, Rougé S, Thonon B. Design methodology and experimental platform for the validation of PCM storage modules for DSG solar plants, 19th SolarPACES International Symposium, Las Vegas, USA, 17-20 september 2013.
- Garcia P, Olcese M, Rougé S. Experimental and numerical investigation of a pilot scale latent heat thermal energy storage for CSP power plant, 20th SolarPACES International Symposium, Beijing, China, 16-19 september 2014.

Future work:

- Further tests on the AlsolenSup demonstrator in the next months.
- Further durability tests on LHASSA experimental facility

CIEMAT-PSA (Spain)

SolarPACES

TASK III-TES

Simulation and test of latent energy storage modules

Challenges:

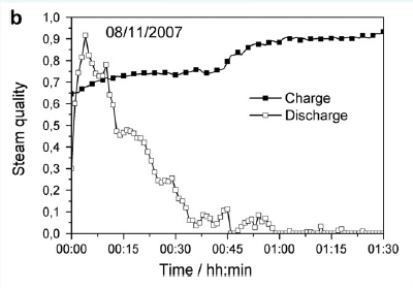
- Designs with enhanced heat transfer for PCMs with low thermal conductivity
- Heat carrier at high pressure (up to 100 bar)=> mechanical stability of design
- High grade of volume change during phase change
- Operation characteristics of storage

State of the art:

- Graphite as heat transfer matrix → only applicable below 250°C and as fin structure, not as expanded matrix.
- Encapsulated concept with metallic envelopes→ relation of containment material to PCM not favorable for high temperature applications. Problems for manufacturing metallic envelopes
- Aluminum fins→ may have problems of corrosion

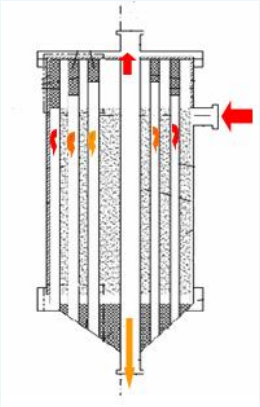
Example of module with graphite fins

- 100 kW module tested at PSA under real DSG conditions
- eu-$NaNO_3$/KNO_3 mixture as PCM sandwiched with expanded graphite
- The model behavior can be represented by temperatures of the middle part
- Power decreases with time ⇨ Real mean power 40-50 kW
- PCM excess not efficiently conferring strong thermal inertia to the whole module



Example of module with spiral geometry

- Large heat exchange area due to spiral geometry -> efficient theoretical heat transfer between PCM and HTF
- 6 kWh module tested at PSA which is an adaptation of a commercial spiral HX
- HITEC salt as PCM
- Experimental results showed stagnation of steam at the upper part and a much lower phase change enthalpy of HITEC.
- No feasible for high steam pressures and high storage capacities



Further information

Contact person: Dr. Esther Rojas; esther.rojas@ciemat.es

- Associated funded project: Research Cooperation in Renewable Energy Technologies for Electricity (REELCOOP), 2013-2017, European Commission,7th FP
- Rodríguez-García, M.M.; Rojas E., Testing a new design of latent storage, ISES EuroSun 2016,
- Rivas, E.; Rojas, E.; Bayon, R.; 2012, Innovating Storage with PCM: Progress in the Design of a New Prototype, 18th SolarPACES International Symposium. Marrakesh, Morocco.
- Rivas, E.; Rojas, E.; Bayón, R. 2011, (~Storage module using latent heat with highly efficient energy transfer). Patent Number: P201131378 (Spain).
- Bayón, R.; Rojas, E.; Valenzuela, L.; Zarza, E.; León, J. Analysis of the experimental behavior of a 100 kW_{th} latent storage system for direct steam generation in solar thermal power plants, Applied Thermal Engineering 30 (2010) 2643-2651.

CIEMAT-PSA (Spain)

SolarPACES

TASK III-TES

Liquid PCMs

Challenges:

- PCM with low thermal conductivity, mostly nitrate salts and their mixtures → heat transfer enhancement required
- Heat carrier at high pressure (up to 100bar) → mechanical stability of design
- High grade of volume change during phase change
- Operation characteristics of storage

State of the art:

Up to now, there is not a good solution for latent heat storage in the range of CSP power plants with direct steam generation

Concept approach:

- Liquid crystals as liquid phase change materials that keep the ability to flow
- Advantages:
  - Heat transfer by convection
  - Storage would operate at constant pressure
- Requirements:
  - Clearing temperature in the steam working range
  - High clearing point enthalpy
  - Low viscosity in all phases
  - Cycling stability
  - Low cost

Current R&D status:

- Collaboration with liquid crystal experts for preparing the most suitable candidates
- Collaboration with other institutions for characterization
- Benzoic acid based liquid crystals prepared and characterized with good thermal properties (245ºC-55 kJ/kg)

Further information:

Contact person: Rocío Bayón; rocio.bayon@ciemat.es

- Bayon R., Coco S. Barcenilla M., Espinet P., Imbuluzqueta G., Hidalgo J., Rojas E.: Feasibility of Storing Latent Heat with Liquid Crystals. Proof of Concept at Lab Scale. Appl. Sci. 2016, 6(5), 121
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- Bayon R., Coco S. Barcenilla M., Espinet P., Imbuluzqueta G., Hidalgo J., Rojas E.: Storing latent heat with liquid crystals. Is it a feasible option? European Conference on Liquid Crystals, Manchester (UK), September 2015. Poster.

- Projects involved: DETECSOL, ALCCONES, STAGE-STE

Future work:

- Synthesis of liquid crystals that can be considered candidates as latent storage media paying special attention to the long term thermal stability.
- Improve characterization and preparation methodologies

CIEMAT-PSA (Spain)

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TASK III-TES

Set-ups for PCM testing: HDR, AGH and SUBMA

Challenges:

Testing PCMs in both air (HDR and AGH) and inert atmospheres (SUBMA)

- Under conditions close to service
- Under accelerated conditions in order to assess long term durability

State of the art:

- PCM performance usually evaluated with differential scanning calorimetry (DSC) or T-history techniques.
- Not many studies carried out for PCMs under service or accelerated conditions

HDR:

- Furnace *under ambient air* atmosphere
- Accurate control of heating rate.
- Sample temperature monitoring
- Thermal cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 10-20 g

AGH:

- Furnace *under ambient air* atmosphere
- Accurate control of heating & cooling rates.
- Sample temperature monitoring
- Thermal cycles up to 350ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 30-40 g

SUBMA:

- Small closed device inside a furnace
- Tests *under inert atmosphere (N_2, Ar)*
- Accurate control of heating rate and gas flow
- Sample temperature monitoring
- Thermal cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 30-40 g

Further information:

- ***HDR* and *AGH*** Contact person: Rocío Bayón; rocio.bayon@ciemat.es
- ***SUBMA*** Contact person: Margarita Rodríguez; margarita.rodriguez@psa.es

- M.M. Rodríguez-García, R. Bayón, E. Rojas. Stability of D-mannitol upon melting/freezing cycles under controlled inert atmosphere. Energy Procedia 91 (2016) 218-225.
- R Bayón, E. Rojas. Feasibility study of D-mannitol as phase change material for thermal storage, AIMS Energy 5 (2017) 404-424.
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TASK III-TES

Phase change storage for delaying power block exhaust heat

Challenges:

- Power block efficiency depends on how good the cooling of exhaust heat is => wet cooling systems are the most widely used cooling systems for STE plants.
- Lack of water in dessert areas prevents the erection of thermal power plants –of any kind- in these areas => industrialized population is limited to the coast.

State of the art:

- Dry and wet-dry cooling systems → their efficiency is defined by a fluctuating ambient temperature.
- Dry and wet-dry cooling systems are power demanders and expensive and has not a mayor reduction in cost due to size.

Concept approach:

- Using a storage system to delay power block exhaust heat to nighttime where both the consumption and ambient temperature are much lower than during daytime.
- Latent storage is selected due to its high storing energy density.

Current R&D status:

- PCM candidates have been selected
- Some of them are under testing to check their reliability under day-cycles.
- Simplified physical model has been erected and served to design the main parameters of storage modules with different storage capacities.

Further information:

- Contact person: Dr. Esther Rojas; esther.rojas@ciemat.es
- Associated funded project: Water Saving for Solar Concentrated Power (WASCOP), 2016-2019, European Commission,H2020
- Pistocchini L, Motta M. Feasibility Study of an Innovative Dry-Cooling System With Phase-Change Material Storage for Concentrated Solar Power Multi-MW Size Power Plant. ASME. J. Sol. Energy Eng. 2011;133(3):031010-031010-8. doi:10.1115/1.4004268.

Future work:

- Systems simulation with different latent storage concept designs will be performed, in order to get an optimization figure according to the location of the CSP plant.

DLR: German Aerospace Center (Germany)

DLR

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TASK III-TES

Extended Finned Tubes

Challenges:

- Material synthesis and characterization => mostly nitrate salts and their mixtures
- Low thermal conductivity of phase change materials (PCM) => heat transfer enhancement
- Challenges for heat transfer enhancement => thermal stability, mechanical stability, good contact to heat exchanger pipes
- High grade of volume change during phase change => avoid material stress
- Operation characteristics of storage

State of the art:

- PCM system with embedded heat exchanger using simple fin geometries without optimization of material use

Concept approach:

- Graphite as heat transfer matrix => only applicable below 250 °C and as fin structure, not as expanded matrix.
- Aluminium fin arrangement (radial or longitudinal fins)
  - Vertical tube arrangement feasible
  - Cost effective concept with extruded longitudinal fins

Current R&D status:

- Finned tube design demonstrated with
  - graphite fins / horizontal tube arrangement (<250 °C)
  - Aluminium fins / vertical tube arrangement (<350 °C)
- Experimental validation of PCM storage concept:
  - 5 lab and pilot test modules with 140-2000 kg PCM with 4 salt mixtures
  - Demonstration of a 14 tons $NaNO_3$ PCM storage (700 kWh, 400 kW, 2949 h, 95 cycles)
- Operation aspects**:** Discharge modes demonstrated in 100 bar water/steam test-loop:
  - Fixed pressure operation => decrease of heat flux over time
  - Sliding pressure => constant heat flux possible
  - Forced and natural circulation
  - Once-through operation and in all modes possible
  - Very high specific heat flux (400 kW average) demonstrated

Further information:

- Contact: Maike Johnson; maike.johnson@dlr.de
- **Laing D, Bauer T, Breidenbach N, Hachmann B, Johnson M.** Development of High Temperature Phase-Change-Material Storages. Appl Energy. 2013;109(September 2013):497–504.
- **Current Projects**: TESIN and DSG-Store (both BMWi federally funded)

Future work:

- Reduction of cost by industrial fabrication of fin/tube arrangement
- Definition of module size for power plant applications
- Demonstration of several modules in a larger scale (ca. 20-30 MWh)
- Optimization of heat exchanger geometry

DLR: German Aerospace Center (Germany)

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TASK III-TES

PCMflux CONCEPT

Challenges:

- In PCM systems with heat exchangers embedded into the storage material the power declines during discharging due to increasing layers of solidified storage material covering the heat transfer surfaces
- The capacity of today's PCM storage systems cannot be increased without increasing also the heat exchanger
- The heat exchanger is not accessible for maintenance
- The charge state cannot be measured

State of the art:

Finned tube heat exchangers are embedded into the storage volume. In order to compensate the increasing heat transfer resistance the heat exchanger has to be oversized to ensure a sufficient heat transfer rate during the discharge process. The costs of the system are dominated by the costs of the heat exchanger

Concept approach:

PCMflux is an active PCM storage concept. The storage material is moved across the heat transfer surface, the thermal resistance remains constant. The transferred power can be adjusted by the velocity of the movement. The PCM is transported in open containers, a thin fluid layer between the containers and the heat transfer surface reduces the thermal resistance and the mechanical friction.

Current R&D status:

- experimental research on heat transfer via an intermediate fluid layer
- development of a simulation tool for the PCMflux concept
- feasibility of the PCMflux concept has been proven in lab-scale
- 10 kW test rig under construction

Further information:

- Contact: Wolf-Dieter Steinmann; wolf.steinmann@dlr.de
- Separation of power and capacity in latent heat energy storage, Energy Procedia 69 (2015) 997-1005
- **Steinmann, W.D**. 'Speichersystem zur Speicherung thermischer Energie', Patent No. DE 10 2004 020 993 B4 2009
- **Research project**: NextPCM funded by the German Federal Ministry for Economic Affairs and Energy

Future work:

- Assessment of alternative geometry options
- Application of various PCMs

ENEA (Italy)

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

SolarPACES

TASK III-TES

Latent Heat Storage with Phase Change Materials and Nanoparticles

Challenges:

- Study and development of Heat Storage Materials with high energy density to reduce the storage volume and associated cost
- Enhancement of the thermal diffusivity/conductivity of the common PCMs (i.e. nitrate salts and their mixtures) to increase the thermal storage efficiency (Nano Enhanced PCMs)
- Improve HTF-PCM heat transfer mechanisms in latent heat thermal storage systems in order to make them more efficient

State of the art:

- PCMs (i.e. nitrate salts and their mixtures) as thermal storage media => low thermal conductivity
- PCMs with dispersed nanoparticles can increase thermal capacity and conductivity => verified only for low temperatures (<200°C)

Concept approach:

- Latent Heat Thermal Energy Storage using PCMs and nanoparticles:
  - ✓ high storage energy density (heat capacity)
  - ✓ high thermal diffusivity
  - ✓ low TES volume
  - ✓ low TES cost

Current R&D status:

- Various combinations of molten salt mixtures and nanoparticles have been analyzed for melting temperatures between 150°C and 600°C
- Enhancements of heat capacity for a phase change storage material composed of Solar Salts and SiO2-Al2O3 nanoparticles and KNO3 and SiO2 nanoparticles and has been verified
- Enhancements of thermal conductivity and diffusivity for a phase change storage material composed by Solar Salts and metallic nanoparticles or CNTs has been verified
- Various mixing protocols have been analyzed and applied to study their effect on the final result
- An experimental analysis of heat transfer in elementary "shell-and-tube" LHTES using solar salts as PCM and/or NEPCM has been conducted by realizing a facility named ATES
- Complex and simplified numerical analyses to characterize the heat exchange mechanisms in a LHTES system during the melting phase were conducted every 30 min

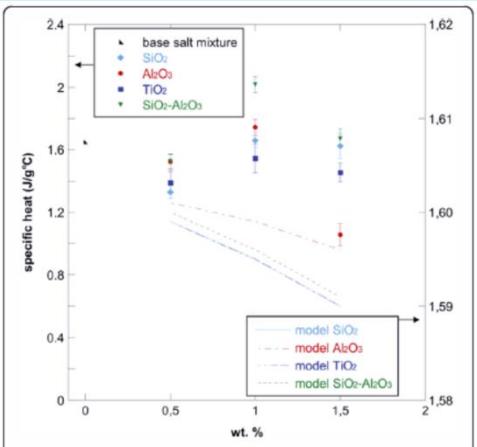
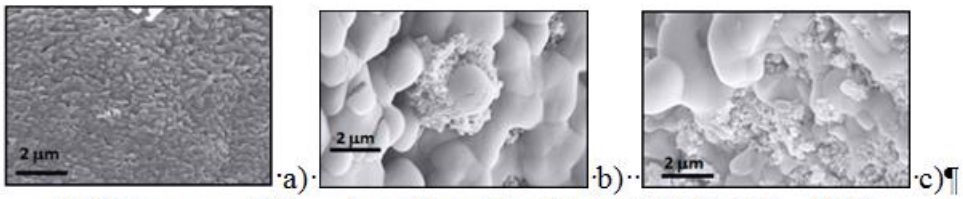
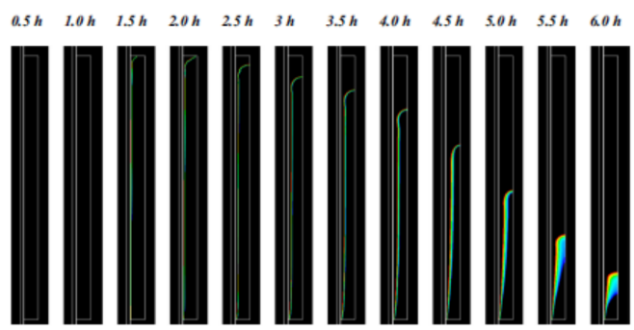


Figure 4 Specific heat values versus particle concentration for $NaNO_3$-KNO_3 binary salt mixture and nanofluids. Experimental data and model predictions.



SEM images of the solar salts with: a) base b) +1% SiO_2–Al_2O_3

ATES Facility



Position of the melting front

Further information:

- Contact person: Dr. Adio Miliozzi, adio.miliozzi@enea.it
- Associated funded project: Energia elettrica da fonte solare, Accordo di Programma ENEA-MISE 2012-2014, Ricerca di Sistema Elettrico, Italian Project
- M. Chieruzzi, G.F. Cerritelli, A. Miliozzi, J.M. Kenny, "Effect of nanoparticles on heat capacity of nanofluids based on molten salts as PCM for thermal energy storage", Nanoscale Research Letters 10/2013; 8(1):448. (ISSN: 1556-276X)
- Chieruzzi, Cerritelli, Miliozzi, Kenny – "Phase change materials based on molten salts and nanoparticles for thermal energy storage" –FeMS EUROMAT 2013, European Congress and Exibition on Advanced Materials and Processes , 8-13 September 2013, Sevilla, Spain
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- A. Miliozzi, R. Liberatore, G.M. Giannuzzi, E. Veca, D. Nicolini, M. Lanchi, M. Chieruzzi, "ENEA research and innovation on Thermal Energy Storage for CSP plants", 16th CIRIAF National Congress, Assisi (PG), 7-9 April 2016
- M. Chieruzzi, E. Veca, A. Miliozzi, L. Torre, "Phase change materials for latent heat storage: research and future trend", 16th CIRIAF National Congress, Assisi (PG), 7-9 April 2016
- A. Miliozzi, M. Chieruzzi, L. Torre, J.M. Kenny, "Nanofluids with Enhanced Heat Transfer Properties for Thermal Energy Storage", In book: Intelligent Nanomaterials, 2nd Edition, Edition: 2nd, Chapter: 10, Publisher: Wiley, Editors: Ashutosh Tiwari, Yogendra Kumar Mishra, Hisatoshi Kobayashi, Anthony P. F. Turner, pp.295-360, ISBN: 978-1-119-24248-2, November 2016
- F Fornarelli, SM Camporeale, B Fortunato, M Torresi, P Oresta, L Magliocchetti, A Miliozzi, G Santo, "CFD analysis of melting process in a shell-and-tube latent heat storage for concentrated solar power plants", Applied Energy 164 (2016) 711–722 (ISSN: 0306-2619)

Future work:

- Synthesis of a molten salt and nanoparticle mixture with lower melting temperature (about 150°C): choice of the components (nanoparticles, CNTs, …) and the mixing protocol
- Realization of an experimental facility (ATES upgrading) able to execute thermal energy charge-discharge tests in a small optimized and modular LHTES
- Development of a numerical model useful for LHTES evaluation and design

Fraunhofer ISE (Germany)

Fraunhofer ISE

SolarPACES TASK III-TES

Latent heat storage with screw heat exchanger

Challenges:

- Development of active latent heat exchanger using a screw heat exchanger: allow transport of PCM during melting and crystallization
- Conduct melting and crystallization of PCM inside screw heat exchanger
- Achieve high thermal powers inside screw heat exchanger
- Development of concept for high pressure steam inside screw heat exchanger

State of the art:

- Passive latent heat storages with embedded heat exchangers (One tank solution). Disadvantages: Decreasing thermal power during storage discharge, capacity and thermal power are coupled directly
- Encapsulated PCM for low temperature applications

Concept approach:

- Transport of solid PCM with transport screws
- Pumping of liquid PCM
- Melting and crystallization of PCM inside screw heat exchanger
- Use of heat pipes for a high pressure concept

Advantages:

- Constant thermal power during storage discharge possible
- Thermal power and storage capacity decoupled
- Advantageous for large thermal capacities
- PCM easily interchangeable

Disadvantages:

- Moving parts (high maintenance effort)
- Measurement of properties of PCM (needed for control of system) in slurry state complicated
- High(er) heat losses compared to passive storage due to larger surfaces

Current R&D status:

- Operational strategies for melting and crystallization developed
- Heat transfer coefficients on PCM side determined for $NaNO_3/KNO_3$
- Development of high pressure concept using heat pipes inside flights ongoing
- Automation of screw heat exchanger ongoing

Further information:

- Contact: Verena Zipf (Verena.Zipf@ise.fraunhofer.de)
- V. Zipf, D. Willert, A. Neuhäuser: Active Latent Heat Storage with a Screw Heat Exchanger – Experimental Results for Heat Transfer and Concept for High Pressure Steam. SolarPaces - Concentrating solar power and chemical energy systems, Capetown, South Africa, 2015.

SUPSI, ETHZ
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SolarPACES
TASK III-TES

Single-tank TES system – Stabilization of HTF outflow temperature during discharging

Challenges:

- Single-tank TES systems have the inherent disadvantage of a decreased HTF outflow temperature towards the end of discharging => HTF temperature stabilization required.
- The solution proposed has to be suitable for high-temperature applications (up to 650°C).
- Experimental and numerical investigation on the combined sensible/latent heat TES.

State of the art:

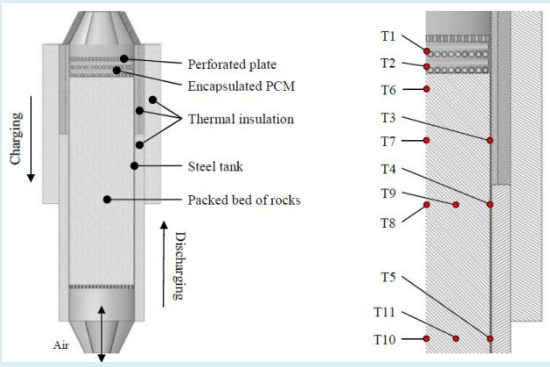
Single-tank TES systems, with a packed bed of low cost filler material, represent an efficient and cost effective solution for storing thermal energy. However, an inherent disadvantage of the sensible heat storage is the drop of the outflow air temperature toward the end of discharge period leading to a non-optimal working condition of the power block.

Concept approach:

- The combined sensible/latent heat TES concept is proposed: a small layer of PCM is added at the top of the packed bed with the aim of stabilizing the HTF outflow temperature during discharging keeping almost unchanged the overall TES cost.

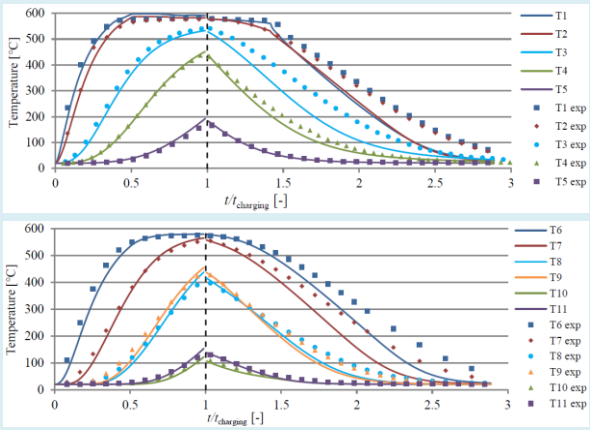
Current R&D status:

- A 42.4 kWh_{th} lab-scale combined TES consisting of a packed bed of rocks and steel-encapsulated $AlSi_{12}$ has been built and tested.

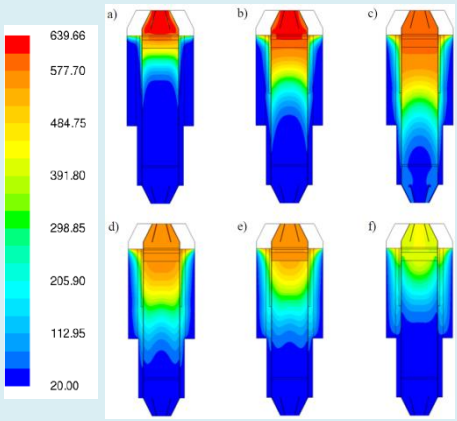


Schematic of the lab-scale combined TES prototype.

- Two numerical modeling strategies has been followed to study the behavior of the combined sensible/latent heat TES: (i) a 1D heat transfer model, suitable for parametric studies thanks to the low computational cost required, and (ii) a 2D computational fluid dynamics (CFD) model, more accurate especially in the case of low vessel-to-particle diameter ratio (as in the experimental prototype) but computationally more expensive.



CFD simulation results (solid lines) VS experimental data (markers); top: PCM and tank wall temperatures, bottom: packed bed.



Temperature contours during charge: a) 1.15 h; b) 2.25 h; c) 3.25 h and discharge: d) 0.55 h; e) 1.15 h; f) 2.25 h.

Further information:

Contact person: Mr. Simone Zavattoni; simone.zavattoni@supsi.ch

- S.A. Zavattoni, L. Geissbühler, M.C. Barbato, G. Zanganeh, A. Haselbacher, A. Steinfeld, “High-temperature thermocline TES combining sensible and latent heat - CFD modeling and experimental validation”, AIP Conference Proceedings 1850, 080028, 2017.
- L. Geissbühler, S. Zavattoni, M. Barbato, G. Zanganeh, A. Haselbacher, A. Steinfeld, “Experimental and Numerical Investigation of Combined Sensible/Latent Thermal Energy Storage for High-Temperature Applications”, CHIMIA, 69 (12), 799-803, 2015.

Future work:

Optimizing the amount of PCM at the top of the packed bed.

UniZar-I3A (Spain)

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Universidad de Zaragoza

SolarPACES

TASK III-TES

THERMAL STORAGE

Challenges:

- Determination of thermophysical and rheological properties of TES materials.
- Lowering the price of TES systems.
- Obtaining recommendations about the most appropriate TES technologies to develop.
- Integration of TES in DHC systems to take advantage of renewable energy resources, residual heat or thermal sources more favorable.
- Use of low cost phase change material emulsions as heat transfer fluids

State of the art:

- Lack of standardized methodologies to characterize TES materials.
- Material cost is critical in some applications.

Concept approach:

- Participation in RRT in the framework of Task 42-Annex 29-IEA-SHC-ECES "Compact Thermal Energy Storage" to develop procedures to characterize TES materials: h(T); λ(T); ρ(T); μ(T)
- Search of low cost and low environmental impact materials to be used as TES materials.
- Accurate comparison of TES systems from the determination of their KPI (such as energy density, heat transfer rate, acceptable maximum heat losses…).
- Integration of a decentralized TES with a low cost PCM emulsion to curtail the peak demand, and to enable the connection of additional buildings in a saturated DH.

Current R&D status:

- Participation in RRT to develop standardized methodologies to characterize TES materials. Coordination of the viscosity measurements.
- Experimental study of a TES system with a low cost PCM emulsion. Different measures are being adopted to improve heat transfer performance. Assessment of KPI for its comparison.
- Commissioning and verification of a T-history installation of high temperature to evaluate enthalpy-temperature curves up to 300ºC.

Further information:

- Contact person: ana.lazaro@unizar.es (Ana Lázaro); monica@unizar.es (Mónica Delgado)
- Lázaro A., Peñalosa C., Solé A., Diarce G., Haussmann T., Fois M., Zalba B., Gschwander S., Cabeza L.F.: Intercomparative tests on phase change materials characterisation with differential scanning calorimeter. Appl Energ 109 (2013) 416-420.
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- Mazo J., Delgado M., Lázaro A., Dolado P., Peñalosa C., Marín J.M., Zalba B.: A theoretical study on the accuracy of the T-history method for enthalpy-temperature curve measurement: Analysis of the influence of thermal gradients inside T-history samples. Meas Sci Technol 26 (12) (2015)
- Delgado M., Lazaro A., Mazo J., Peñalosa C., Dolado P., Zalba B.: Experimental analysis of a low cost phase change material emulsion for its use as thermal storage system. Energ Convers Manage 106 (2015) 201-212.
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Laboratory of characterization of thermophysical and rheological properties:

http://i3a.unizar.es/sites/default/files/documentos/laboratorio_ingenieria_termica_GITSE.pdf

THERMOCHEMICAL STORAGE

CEA – LITEN (France)

FROM RESEARCH TO INDUSTRY

SolarPACES

TASK III-TES

Thermochemical Heat Storage for CSP

Challenges:

- Cycling and lifetime of the storage media,
- Continuous operation of the storage process,
- Discharging temperature at the same level as charging temperature,
- Demonstration of feasibility at prototype scale and realistic conditions.

State of the art:

- High temperature thermochemical storage is currently at the laboratory scale.
- Solids/Gas reaction of $CaO + H_2O \leftrightarrow Ca(OH)_2$

Concept approach:

Daily and seasonal heat storage using the reversible reaction $CaO + H_2O \leftrightarrow Ca(OH)_2$:

- Non or slightly pressurized bubbling or circulating Fluidized bed reactor.
- Non expansive natural lime as storage material.
- Doping of the materials to improve mechanical and chemical properties;
- Study of the chemical and/or mechanical performances degradation of the storage material. Attrition, sintering, thermal breakage of the solid particles.

Current R&D status:

- A batch bubbling fluidized bed at room temperature and atmospheric pressure for fluidization characterization (pressure drop, minimal velocity of fluidization and transport, attrition, particles cohesion)
- A batch bubbling fluidized bed at high temperature and atmospheric pressure for thermochemical characterizations :
- 5 kW (2-3 kg solid), ≤ 1 m/s, up to 500 °C, ≤ 75% P_{steam}
- A continuous bubbling fluidized bed at high temperature and atmospheric pressure
- 5 kW reaction / 15 kWh (20 kg/h solid), ≤ 2 m/s, ≤ 600°C, ≤ 100% P_{steam}
- A 1D numerical model of a batch bubbling fluidized bed reactor coupling thermal, chemical and hydrodynamic laws has been developed.

Further information:

- Contact person: Sylvie Rougé ; sylvie.rouge@cea.fr
- A review on high temperature thermochemical heat energy storage; P. Pardo, A. Deydier, Z. Anxionnaz-Minvielle, S. Rougé, M. Cabassud, P. Cognet; Rene. Sust. Energy. Rev. Vol: 32 Issue: 2 (2014) p. 591-610.
- Pardo, P.; Anxionnaz-Minvielle, Z.; Rougé, S.; Cognet, P.; Cabassud, M. Ca(OH)2/CaO reversible reaction in a fluidized bed reactor for thermochemical heat storage. Sol. Energy 2014, 107, 605.
- Y.A. Criado, M. Alonso, J.C. Abanades, Z. Anxionnaz-Minvielle; Conceptual process design of a CaO/Ca(OH)2 thermochemical energy storage system using fluidized bed reactors; App. Therm. Eng., 73, 1085–1092 (2014).
- Y.A. Criado, A.Huille, S. Rougé, J.C. Abanades; Experimental investigation and model validation of the CaO/Ca(OH)2 fluidized bed reactors for thermochemical energy storage applications, Chem. Eng. J., submitted June 2016.
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- Continuous CaO/Ca(OH)2 fluidized bed reactor for energy storage: first experimental results and reactor model validation, Rougé, S.; Criado, Y.A. ; Soriano, O.; Abanades, J.C., Industrial & Engineering Chemistry Research 56 (4), pp. 844-852 (2017).

Future work:

- Doped materials will be tested in steady state operation with the continuous bubbling fluidized bed.

DLR: German Aerospace Center (Germany)

DLR

SolarPACES

TASK III-TES

THERMOCHEMICAL ENERGY STORAGE WITH $Ca(OH)_2$

Challenges:

Material:

- Low cost material that is already available in large industrial scale but so far not used for thermal energy related applications. Main challenges are the morphological changes within the bulk during the reaction as well as the in general very small particle diameter.

Reactor:

- Heat transfer from reactive powder to the HTF / Reaction gas supply and distribution
- Volume change during chemical reaction

Integration:

- Equilibrium temperature of the chemical reaction
- Storage and supply of reaction gas

State of the art:

- 10 kW / 10 kWh system for $Ca(OH)_2$ in operation since 2013
- 10 kW / 100 kWh system for $Ca(OH)_2$ with a moving bed operated first time in 07/ 2015

Concept approach:

- The main idea is the detachment of the simple storage from the reaction zone that is due to above mentioned challenges in general more complex.
- Based on this clear separation, it is possible to store thermal energy at ambient conditions
- One main challenge is the adjustment of proper reaction conditions in moving material

Current R&D status:

- Experimental set-up available in 100 kWh scale. Current work focuses on continuous operation and optimization of secondary components.
- Reduction of reactor complexity along with an increase of powder density
- System integration of water vapor
- Material modification in order to facilitate the heat exchange btw. HTF and reacting powder

Further information:

- Contacts: Marc Linder; marc.linder@dlr.de) and Matthias Schmidt; matthias.schmidt@dlr.de
- **Schmidt et al**., (2013) Experimental results of a 10 kW high temperature thermochemical storage reactor based on calcium hydroxide. Applied Thermal Engineering (62), 553-559. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2013.09.020
- **Linder et al.** (2014) Thermochemical Energy Storage in kW-scale based on CaO/Ca(OH)2. Energy Procedia (49), 888-897. Elsevier. DOI: 10.1016/j.egypro.2014.03.096

Future work:

Continue with the detachment of power and capacity by transport of the reaction material from a simple storage through the complex reaction zone (reactor). Take potential material modifications into account. Integration aspects, e.g. into CSP plants. Take advantage of chemical reaction - re-think CSP for thermochemical storages.

ENEA (Italy)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

SolarPACES

TASK III-TES

Chemical heat storage by reversible chemical reactions

Challenges:

- Assessment of a compact heat storage system, especially designed to be used for seasonal heat storage.

State of the art:

- Even if the analysis of possible thermochemical storage systems started in the 1970s (sulfates, calcium carbonate or hydroxide, ammonia, cobalt oxide, manganese oxide, etc), only recently have thermochemical reactions been reconsidered for the purpose of high temperature heat storage.
- The development of these storage systems is still at an early stage because of material degradation and complex technology
- The analysis is currently focused on the cycling behavior (reversibility and degradation over large numbers of cycles) and kinetics of charging and discharging steps.

Concept approach:

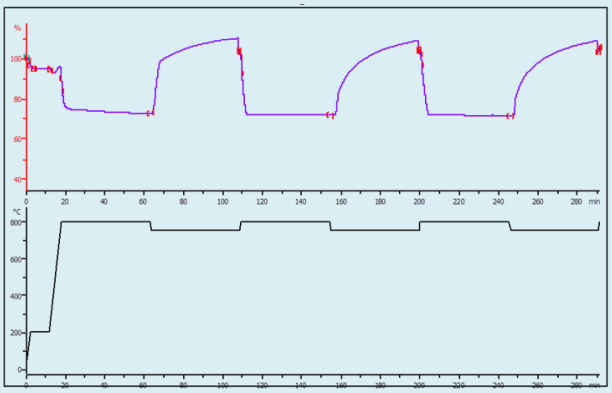
- The attention was focused on the following reversible reactions, even considering synthetic materials capable of standing continuous and repeated cycles:

  $CaO + CO_2 \rightarrow CaCO_3$ (to be integrated with central tower plants)

  $CaO + H_2O \rightarrow Ca(OH)_2$ (to be integrated with parabolic trough plants)
- Besides the experimental activity, a theoretical analysis was performed, aimed at the definition of suitable process schemes for the solar plants-TCS integration, with the design of the coupling interfaces (heat exchangers, direct contact reactors, adiabatic reactors)
- Both open and closed cycles were analyzed, considering also the hypothesis of charging and discharging facilities located in different places.

Current R&D status:

- Validation and collection of thermo-physical properties and kinetic data concerning the $CaO/Ca(OH)_2$ and $CaO/CaCO_3$ systems
- Kinetic characterization of the calcium carbonate reacting system (calcination and carbonation steps)
- Modelling of a reactor module for the analysis of the charging and discharging steps dynamics
- Design of possible process schemes for the integration of thermochemical storage with the central tower technology (calcium carbonate) and the parabolic trough technology (calcium hydroxide), with the definition of the operating parameters in nominal conditions.



Carbonate calcium reacting system: thermogravimetric test of charging and discharging steps ($T_{charg.}$ 800°C; $T_{disch.}$:750°C)

Further information:

- Contact person: Michela Lanchi ; michela.lanchi@enea.it
- The activity was funded by the DTE ENEA department

Future work:

- Design of a feasible solar-powered reactor both for carbonate and hydroxide systems
- Dynamic analysis of the integrated solar plant/thermochemical unit
- Techno-economic evaluation of the storage system

TAU: Tel Aviv University (Israel)

TASK III-TES

Thermo-electro-chemical storage (TECS) of solar energy

Challenges:

Solar thermal electricity generation with storage is not yet competitive, and its conversion efficiency is relatively low for the leading technologies.

State of the art:

CSP plants rely on a thermo-mechanical conversion with steam Rankine cycle; thermal storage relies on two tanks of molten salt with heat exchange to the steam cycle, and in some cases additional heat exchange to the solar field HTF. Alternative cycles (e.g. CO_2 or air Brayton cycle) and alternative storage methods (PCM or chemical storage cycles) are under development and not yet available.

Concept approach:

The proposed approach is to eliminate the thermo-mechanical cycle and replace it with thermally driven electro-chemical conversion. The TECS cycle contains a high temperature solar reactor driven by a CSP concentrator (dish or heliostat field) for charging, storage tanks for charged and discharged components, and an electrochemical cell for discharging (electricity generation). Potential advantages include: power generation without complex heat engines, avoiding multiple fluid loops, and potentially high conversion efficiency.

Current R&D status:

A preliminary thermodynamic analysis including several candidate materials has shown that the theoretical conversion efficiency of the TECS cycle can be very high. A paper on the analysis is in preparation.

Further information:

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Future work:

Future work includes: analysis with more detailed and realistic cycle design; investigation of additional candidate materials; and experimental validation of the thermo-chemical charging reaction. Following these steps, a lab scale demo of a full cycle should be considered.