Thermochemical Energy Storage System for High Temperature Compatibility and Cost Efficiency

S. ARUMUGAVEL
SSM Polytechnic College, Tamilnadu, India

Abstract -- Concentrated solar thermal systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electricity is generated when the concentrated light is converted to heat, which drives a heat engine connected to an electrical power generator or powers a thermochemical reaction. This facilities require an energy storage system to be economical, sCO2 power cycles operating at high temperatures have potential to significantly increase the thermal efficiency of a solar power plant and however, currently available energy storage systems are costly and limited to about 500 C. This article provide the solution to overcome the highlighted problems with operation at high temperatures compatible with sCO2 power cycles.

Indexed Terms: Thermochemical Storage System for High-Temperature, Concentrating Solar Power Facilities

I. INTRODUCTION

Fluid from the low-temperature tank flows through the solar collector or receiver, where solar energy heats it to a high temperature, and it then flows to the high-temperature tank for storage. Fluid from the high-temperature tank flows through a heat exchanger, where it generates steam for electricity production. Thermal energy storage is like a battery for a building's air-conditioning system. It uses standard cooling equipment, plus an energy storage tank to shift all or a portion of a building's cooling needs to off-peak, night time hours. During off-peak hours, ice is made and stored inside IceBank energy storage tanks. If energy is stored, it cannot be called heat. It becomes thermal energy. Thermal energy can be stored by taking a substance and using the energy to heat it and then placing it in a thermally insulated container. This energy will be stored and will cause an increase in the temperature of the substance. A thermal store is a way of storing and managing renewable heat until it is needed. In a domestic setting, heated water is usually stored in a large well-insulated cylinder often called a buffer or accumulator tank. A thermal store can provide: Space heating and mains pressure hot water.

A. Thermo-chemical storage

Thermal energy storage includes a number of different technologies. Thermal energy can be stored at temperatures from -40°C to more than 400°C as sensible heat, latent heat and chemical energy (i.e. thermo-chemical energy storage) using chemical reactions [1]. Thermal energy storage in the form of sensible heat is based on the specific heat of a storage medium, which is usually kept in storage tanks with high thermal insulation. The most popular and commercial heat storage medium is water, which has a number of residential and industrial applications. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications. However, TES systems based on sensible heat storage offer a storage capacity that is limited by the specific heat of the storage medium. Phase change materials (PCMs) can offer a higher storage capacity that is associated with the latent heat of the phase change. PCMs also enable a target-oriented discharging temperature that is set by the constant temperature of the phase change. Thermo-chemical storage (TCS) can offer even higher storage capacities. Thermo-chemical reactions (e.g. adsorption or the adhesion of a substance to the surface of another solid or liquid) can be used to accumulate and discharge heat and cold on demand (also regulating humidity) in a variety of applications using different chemical reactants. At present, TES systems based on sensible heat are commercially available while TCS and PCM-based storage systems are mostly under development and demonstration.

B. Performance

Thermal energy storage includes a number of different technologies, each one with its own specific performance, application and cost. TES systems based on sensible heat storage offer a storage capacity ranging from 10-50 kWh/t and storage efficiencies between 50-90%, depending on the specific heat of the storage medium and thermal insulation technologies. Phase change materials (PCMs) can offer higher storage capacity and storage efficiencies from 75-90%. In most cases, storage is based on a solid/liquid phase change with energy densities on the order of 100 kWh/ m3 (e.g. ice). Thermo-chemical storage (TCS) systems can reach storage capacities of up to 250 kWh/t with operation temperatures of more than 300°C and efficiencies from 75% to nearly 100%. The costs for PCM and TCS systems are in general higher. In these systems, major costs are associated with the heat (and mass) transfer technology, which has to be installed to achieve a sufficient charging/discharging power. The economic viability of a TES depends heavily on application and operation needs, including the number and frequency of the storage cycles.

C. Limitation

The storage of thermal energy (typically from renewable energy sources, waste heat or surplus energy production) can replace heat and cold production from fossil fuels, reduce CO_2 emissions and lower the need for costly peak power and heat production capacity. It has been estimated that around 1.4 million GWh per year could be saved—and 400 million tonnes of CO_2 emissions avoided—in the building and industrial sectors by more extensive use of heat and cold storage. However, TES technologies face some barriers to market entry. In most cases, cost is a major issue. Storage systems based on TCS and PCM also need improvements in the stability of storage performance, which is associated with material properties.

D. Types of Thermal Energy Storage

There are three types of Thermal Energy Storage (TES) systems, depending on whether they use sensible, latent or chemical heat [2].

Sensible heat thermal storage is achieved by heating the storage medium (liquid sodium, molten salt or pressurised water) and increasing its energy content but not changing state during accumulation. Energy is released and absorbed by the medium as its temperature reduces and increases respectively. Sensible heat can be stored in either solid media (in packed beds, e.g. concrete, requiring a fluid to exchange heat) or in liquid media such as molten salt or pressurized water.

On the other hand, latent heat is associated with changes of phase. Energy required during charging is used to convert a solid material in a liquid material (such as paraffin wax), or a liquid material in to a gas. Phase change materials have the benefit of high thermal capacity but have the drawback of degrading performance after a number of freeze-melt cycles. In order to use latent heat storage, the storage material should have a melting temperature within the range of the charging and discharging temperatures of the Heat Transfer Fluid (HTF). As thermal storage has not been previously investigated for an industrial application, this limits the availability of suitable latent heat storage systems.

Similarly, endothermic chemical reactions require a specific temperature at which a chemical product is dissociated in a reversible chemical reaction [3] and heat is retrieved when the synthesis reaction takes place. The development of such Thermochemical reactions is already at a very early stage and as the reaction temperature should lie within the charging and discharging temperature of the HTF, therefore the use of such technology needs to be case specific. Hence, out of the options considered, it was most viable to use sensible heat storage, such as pressurised water and molten salt. In the case where steam is being used as a working fluid, excess steam can be stored in a steam accumulator as pressurised water. Direct storage of steam gives the benefit of fast reaction times and high discharge rates. Excess steam is stored in a pressurised vessel with a mass of water inside the capacity of which is limited by the volume of the pressure vessel. Molten salt can be used as a secondary storage, using heat exchangers for charging and discharging the medium, while using steam as the HTF. Molten salt has the benefits of high volume specific thermal capacity, is readily available and is relatively cheap but it has the drawback of a high freezing temperature (120-220oC). This means that special care must be taken to ensure that the salt does not freeze (solidifies). Routine freeze protection operation increases maintenance and operational costs.

II. ADVANTAGES AND LIMITATIONS

Advantages

- Potential for very high volumetric energy densities
- Wide and dynamic range of operating temperatures
- Very high exergetic efficiencies, isothermal energy storage and delivery

Limitations

- Difficulties maintaining durability of storage media over large number of charge/discharge cycles

Desirable Reaction System

- Highly reversible
- High heat of reaction
- Reaction equilibrium occurs in relevant temperature range
- Low cost, non-toxic storage media
- Minimal required balance of plant

The reversible carbonation of Calcium Oxide

CaO + CO2 <-> CaCO3 + 180 KJ

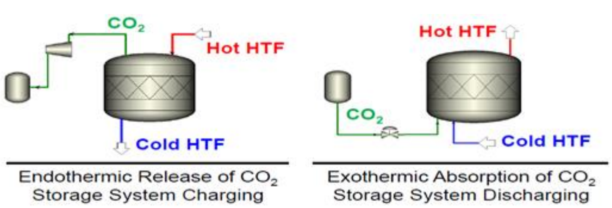

Fig 1: The reversible carbonation of CaO

- Reaction fully reversed by temperature and/or pressure swing
- High heat of reaction
- Reaction equilibrium occurs in relevant temperature range of 650-800oC
- Low cost, non-toxic, abundant storage media ~$50/ton
- Capacity and durability are key challenges

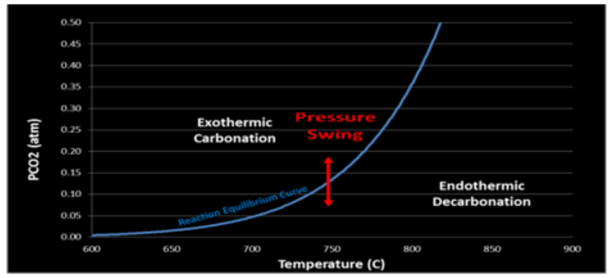

Fig 2: Reaction fully reversed - Pressure swing

III. PROCESS FLOW

- Optimize baseline CaO sorbent composition and demonstrate required high capacity and negligible degradation over >100s of accelerated cycles in TGA testing at sCO2 cycle-compatible temperatures (720-750 C)
- Investigate and develop methods of in-situ capacity recovery if sorbent degrades due to accidental temperature increase
- Design, build and test bench-scale heat exchanger reactor system (HxRx) to demonstrate required sorbent capacity and durability over >100s of accelerated cycles as well as real time (extended) cycles
- In parallel, discuss HxRx designs with commercial Hx manufacturers and conduct techno-economic evaluation to optimize HxRx and balance of plant design
- Build and validate HxRx Multiphysics mathematical models using Comsol with TGA and bench-scale data to assist in scale up
- Scale up sorbent manufacture to ton quantities with help from a manufacturer
- Design, build and demonstrate a field scale system (0.5 to 1 MWh) to allow technology to advance to large pilot scale , Target: Energy efficiency >90 %

The required high sorbent durability and capacity was achieved by optimizing composition, and preparation and activation conditions

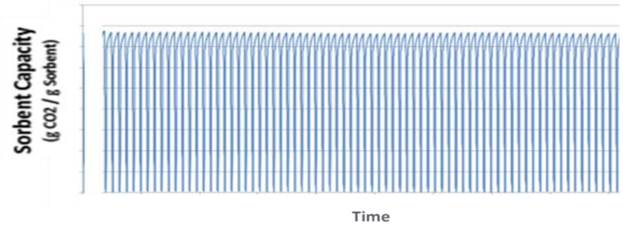

Fig 3: Durability Test Results

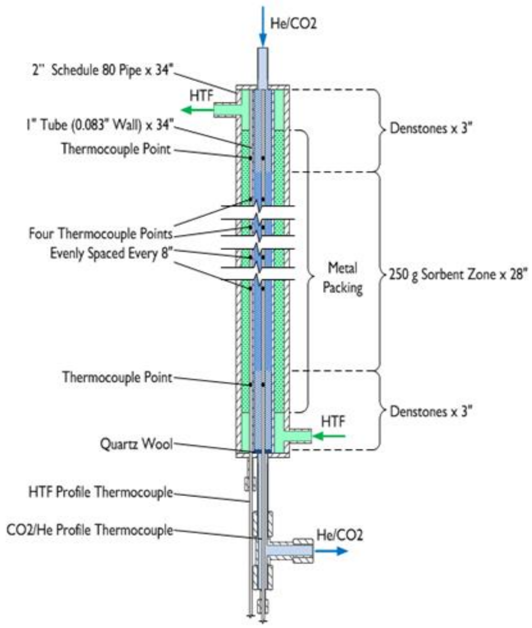

Fig 3: Bench-scale Reactor System

IV. CURRENT STATUS OF SORBENT TESTING

- Bench-scale system has been built and fully commissioned using inert material in place of CaO sorbent
- Methods have been investigated for recovery of sorbent activity after intentional degradation using high temperature exposure
- Optimized sorbent has been scaled up to kg quantities and will be prepared for bench-scale testing. Multi-cycle durability testing will begin this month.
- A 3D finite element model with coupled heat and mass transfer has been built for the bench-scale reactor. It is being validated with inert material in the place of the sorbent to isolate the effects of heat transfer boundary conditions from the reaction kinetics of the sorbent.
- Cost sensitivity analyses are being performed and a Technology Transfer Package is being prepared

V. CONCLUSION

The newly build system with sorbent material has helped to overcome the problems highlighted in abstract. The optimized sorbent energy storage on the system would be economical as well facilitate with hold the required energy for future demands. sCO2 power cycles has been able to operate in higher temperature than the traditional systems and limitation has been resolved. In parallel, a number of potential commercial embodiments of the storage system compatible with a sCO2 power cycle were conceived and evaluated. A preferred configuration was selected.

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