DEVELOPMENT OF A DIRECTLY IRRADIATED FLUIDIZED BED AUTOTHERMAL REACTOR FOR CONCENTRATED SOLAR THERMAL TECHNOLOGIES

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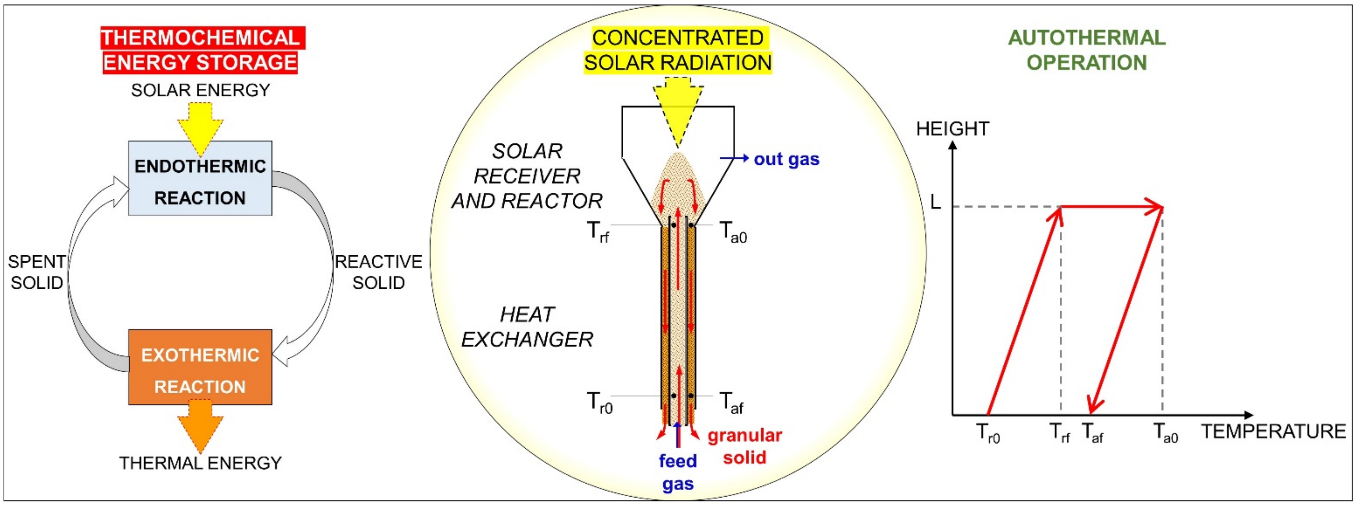
All over the world the effects of pollution are becoming unignorable and the concern about the environmental sustainability of our society is getting more and more attention. Anthropogenic CO_2 emissions are driving climate change and represent today a critical issue. A transition from fossil to renewable resources for our energy and manufacturing industries is necessary and many countries are taking decisions to this end. In 2015 the Paris Agreement laid down the commitment to limit global warming below 2°C by reducing CO_2 emissions. In accord to this purpose, the European Commission has plans to reach carbon neutrality by 2050, that is the main objective of the European Green Deal. Among other renewable resources, solar energy will play a crucial role in the following decades, to achieve this result.

Concentrating Solar Thermal (CST) technology represents a simple solution to exploit solar energy, with easily affordable materials. Based on a principle dating back to Archimedes, it consists of a set of sun-tracking mirrors, opportunely sized, shaped and positioned to collect and concentrate solar radiation onto a receiver. The receiver can be any device with the task to absorb and make available solar energy as heat. The coupling with Thermal Energy Storage (TES) systems allows to overcome the major drawback of the discontinuity of solar radiation intensity, due to weather conditions and Earth rotation. Currently at commercial scale, the use of molten salts as heat carrier and large adiabatic storage tanks is a proven technology. However, the upper limit of 565 °C, due to salt degradation, limits the efficiency of the thermodynamic cycle for power generation and the density of stored energy. The use of granular solids as heat carrier can overcome this limitation, as temperatures of over 1000 °C can be easily tolerated by solid particles. Moreover, Thermochemical Energy Storage (TCES) would allow larger densities and virtually unlimited time scale of storage and dispatchability. It consists in exploiting solar energy to sustain an endothermic chemical reaction, thus storing energy in the reaction products. TCES processes usually require two reactive steps, performed cyclically: the endothermic step for the storage of solar energy and an exothermic one for the regeneration of a reactant and the exploitation of stored energy. An example is the Calcium Looping, in which the endothermic step is the calcination of calcium carbonate, and the exothermic one is its reverse reaction, the carbonation of calcium oxide. This process is also of interest for Carbon Capture. Similar processes can be performed by substituting the calcium oxide with other alkaline metal oxides, or CO_2 with H_2O, performing hydration/dehydration cycles. These processes are apt for stationary energy production. But TCES can also aim at the production of solar fuels for the transportation sector, for example by thermal splitting of CO_2 and H_2O. In this case the endothermic reaction is the reduction of a transition metal oxide, referred to as oxygen carrier. Then the oxygen-depleted oxide reacts with CO_2 and H_2O, producing synthesis gas (CO and H_2), that can be employed for the production of synthetic fuels. The reduction of the oxygen carrier usually requires temperatures over 1000°C. Methane can be added, acting as reducing agent and giving partial oxidation products. This allows to decrease the reaction temperature and increase the production of synthesis gas. By considering the global balance of the cycle, methane reforming is performed, so this process is referred to as Chemical Looping Reforming. In order to keep negative CO_2 emissions, bio-gas could be used as source for methane. Alternative ways of producing solar fuels are solar pyrolysis and gasification. The replacement of fossil sources with biomass in these last processes can zero the carbon footprint.

All cited TCES processes involve gas-solid chemical reactions, so multiphase reactor design plays a key role for the success of this technology. The scope of the PhD research is the development of a novel fluidized bed for high temperature operation, named Directly Irradiated Fluidized Bed Autothermal Reactor, with application to TCES.

The Directly Irradiated Fluidized Bed Autothermal Reactor (DIFBAR) basically consists of a vessel with a conical shaped bottom, sealed at the top with a transparent optical window, that serves as solar receiver/reactor, and two vertical coaxial tubes (internal one referred as riser, external as annulus,) connected at the bottom of the receiver, that serve as a double-pipe counter-current heat exchanger. The bed material is transported by a fluidizing gas stream through the riser into the receiver, where the solid particles are exposed to a flux of concentrated solar radiation and the chemical process at high temperature takes place. From the receiver the solid particles fall by gravity into the annulus, whereas the gas leaves the system through a lateral tube. The bed material descends through the annulus as a moving bed, transferring its sensible heat to the up-flowing fluidized bed in the riser. In this way, the solid reactant feed is pre-heated, saving the energy input necessary to reach the elevated temperatures required for a TCES process, according to the principle of an autothermal reactor. Autothermal operation is assumed to be the key, to attain a high energy efficiency and thus to minimize the size of the CST facility per unit of stored energy.



The scope of the PhD project is the full demonstration of the operating principle of the DIFBAR and its application to a TCES process, through the design, realization and operation of a new experimental prototype. Further results that are pursued are pushing forward the understanding of its fluid dynamic behavior and closing an energy balance to assess its efficiency as solar receiver and reactor.

The first year of the PhD project was devoted to bibliographic research, modeling and designing. Studying of the scientific literature and modeling activities will continue throughout the research period on the sidelines, to support the main activities. The PhD project inherited a simple model of the thermal energy transfers inner to the device, that was primarily used to determine the length of the heat exchanger (1 m). This model was also extended to study the application to limestone calcination and the results were gathered in a paper presented at the 15th SDEWES conference and published as special issue by the scientific journal Energy Conversion and Management. A simulator of concentrated solar radiation has been assembled, consisting of a 10 kW_{el} Xenon arc lamp coupled with an elliptic reflector. Modularity and flexibility are key features of the new prototype: every part is conceived as removable and replaceable. This will allow to test three different schemes. In a first scheme solid particles are withdrawn from and re-injected in a same reservoir, thus recirculating in a closed loop. An open loop scheme has also been conceived, for a continuous processing of solid particles. And finally, a scheme is thought, to screen possible photolabile reactants or products, or to operate the receiver without an optical window, by physically separating the reaction zone from the receiver. Stainless steel is chosen as main material, in order to easily machine and assemble the various parts.

By the end of the second year, the new prototype shall be complete and operative and a series of experimental campaigns shall start. According to the objectives of the project, a first campaign shall assess the fluid dynamic characteristics, by pressure measurements, video analysis and tracing techniques. A second campaign will follow, investigating the thermal behavior of the device, with the sun simulator as heat source. A first assessment of the energy efficiency under non-reactive conditions will be obtained, by closing an energy balance with collected temperature data. At last, TCES will be studied, with many possible processes to choose from. Calcium Looping will be studied as it is a benchmark of the research group. Under study is also the Chemical Looping Reforming of methane with a laboratory-made perovskite, as oxygen carrier.

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