Optimizing the integration of a chemical process with a concentrated solar power source: the SOL2HY2 project

CSP technology

The exploitation of solar thermal energy is increasingly spreading worldwide and can provide heat at low, medium and high temperatures. Therefore, this renewable energy source can be used for several purposes, ranging from household to industrial applications.

Concentrated solar power (CSP) plants use mirrors to concentrate the sun rays on a smaller surface target, the receiver, and provide high-temperature heat to a process or heat transfer fluid. In currently-operating CSP installations, the heat collected is mainly used to produce electricity from a renewable, carbon-free source through a thermodynamic cycle. For this application, solar troughs are now the most mature and verified technology, with several hundred MWel in operation especially in the south-western United States and Spain.

The heat collected in a CSP plant can also be used to power a chemical process. In this field, an application on which many research institutions and private companies have been working for several years is the production of hydrogen from the splitting of water, in order to produce a clean, efficient and carbon-free fuel.

The main issue related to the use of solar thermal energy is the intrinsic discontinuity of the solar radiation. Indeed, most of the processes that could be powered by solar energy must be operated continuously and cannot afford daily start-up and shut-down operations both for economic and technical reasons. This is particularly true when solar heat must be used in a chemical plant.

SOL 2HY2
Solar To Hydrogen Hybrid Cycles

Heat storage systems

In order to solve the continuity issue, CSP plants may be coupled with a heat storage system that accumulates heat in a high heat capacity medium to deliver energy even when the sky is cloudy or after sunset.

Such thermal storage significantly improves the "capacity factor" of the plant, as well as the integration with the power grid and economic competitiveness, but requires the solar field to be oversized compared to its nominal power output. A trade-off must be evaluated between the increase in cost associated with the thermal storage system and the economic benefit resulting from the increased energy production. Molten nitrate mixtures provide a viable large scale thermal storage medium, reaching storage efficiencies higher than 99% and the possibility to provide 24 h solar heat at constant rate due to their high heat capacity per unit volume. Compared with organic oils, molten nitrate mixtures are stable at high temperatures (up to 600°C), relatively inexpensive and widely available, not flammable, and have minor environmental impact; moreover, these molten salts have very low vapour pressure (i.e., do not require pressurized systems) and low corrosion rates with common-piping materials. One of the most promising molten salt mixtures for solar applications is $NaNO_3$/ KNO_3 (60/40 w/w), often referred to as ''solar salt,'' which has already been positively tested as solar heat carrier and heat storage medium up to 565°C in different CSP plant locations, based on both solar troughs and towers.

The SOL2HY2 project

The SOL2HY2 (Solar to Hydrogen Hybrid Cycle) is focused on the

Fig. 1 - Hybrid sulfur chemical cycle powered by solar energy

production of hydrogen through the so-called hybrid sulphur (HyS) chemical cycle powered by solar energy. The HyS process consists of a set of chemical reactions involving sulphur compounds whose net result is the splitting of water into hydrogen and oxygen, while other components are continuously recycled. The energy input required by the process is provided as electric power in the section where hydrogen is produced, and high temperature heat in the section where oxygen is produced. Originally designed to run on a continuous nuclear heat source, the HyS poses several technological and flowsheeting issues in order to be powered by solar energy. Among these, the process flowsheet must be optimized to minimize the net energy consumption and reduce the required size of the solar field and heat storage system. Integration of the chemical plant with CSP is another crucial aspect to be analysed. Several commercial and free software applications like process simulators are available to help design and optimize the chemical process and the CSP system separately; however, the whole plant optimization requires a combination of the results of the simulations of both components into a single framework. The use of metamodels is a viable technique to handle this problem.

Metamodeling and multi-objective optimization

As in the case of the SOL2HY2 project, very often, in engineering sciences, data have to be fitted to have a more general view of the problem at hand. These data usually arise from a series of experiments, both physical and virtual, and surface fitting is the only way to get relevant and general information from the system under examination. Interpolation is a major technique for constructing mathematical models which can substitute complex models in real-case applications: when the original model is complex, or when it requires long and costly evaluations, a simplified model of the original is required.

This model-of-the-model is often called a metamodel (or response surface), and the metamodeling technique is widely used in industrial applications Metamodelling is able to tackle multidimensional data fitting problems and since optimization frequently requires many evaluations of the system's performance, the speedy performance delivered by the metamodel is, in many situations, the only practical way of delivering such optimizations. Hence we can create metamodels both of the entire system for the production of hydrogen powered by solar energy and of smaller blocks of the process to get a better knowledge of the problem. These response surfaces will allow us to predict the behaviour of the process at untried sites (varying the input parameters in their feasibility ranges) and therefore to perform multi-objective optimization in order to find the best configuration of our system, i.e. the one that minimizes costs and energy consumption and maximizes the efficiency of the process.

It is very uncommon to tackle problems concerning only a single objective when dealing with real-world industrial applications: generally multiple, often conflicting, objectives arise naturally in most practical optimization problems; thus several multi-objective optimization methods have been developed. Many of these algorithms are based on a stochastic search approach such as evolutionary algorithms, simulated annealing and genetic algorithms.

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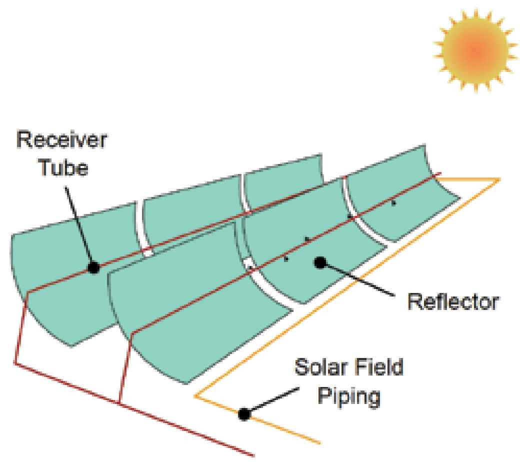

Fig. 2 - Parabolic solar troughs

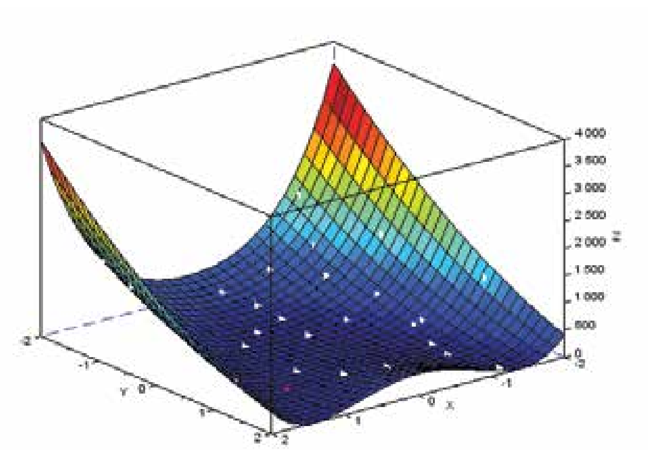

Fig. 3 - Metamodel interpolating a given set of data