Around the Clock Solar Power

Thermal modeling enabled the optimization of a critical drainage system for Archimede, the first Concentrating Solar Power (CSP) plant in the world to use molten salt for heat transfer as well as storage and to be integrated with an existing combined cycle gas facility.

BY JENNIFER HAND

Situated on the east coast of Sicily, this innovative industrial demonstration plant uses Parabolic Trough CSP technology to generate electricity during sunny hours as well as under overcast conditions or at night. Jointly developed by Italian utility ENEL and the Italian National Agency for New Technologies ENEA, it began operating in July 2010 and is named after the mathematician and engineer Archimedes who lived in the nearby town of Syracuse.

Archimede incorporates 30,000 square meters of reflective parabolic mirror surface, in the shape of troughs. The sun's rays are concentrated onto long thin tubes, which together make up a receiver pipeline running along the inside of the curved surfaces and stretching for 5,400 meters. This pipeline contains a heat transfer fluid made of 60% sodium nitrate and 40% potassium nitrate, commonly used as fertilizer.

During the start-up of the power plant this mixture is heated to at least 240° C (464° F) so that it melts and can pass into the tubes. Once it is molten, it is heated further by the sun and channeled to a dedicated steam generator where it produces high-pressure steam that drives a turbine in the adjacent combined-cycle power plant.

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The Molten Salt Advantage

Mainly located in the US and Spain, there are several CSP plants already in operation. They all depend on pipes filled with diathermal oil to absorb solar heat and older CSP plants can only operate in the daytime under direct sunlight. Newer plants have extended their operating hours through the use of molten salt as a medium for storing heat in large, well-insulated tanks.

Using molten salt for heat capture as well as storage has several advantages over pressurized oil. Molten salt operates at 550° C (1022° F) compared with oil at 390° C (734° F) so power output goes up, maximizing energy efficiency and potentially reducing the consumption of fossil fuels. The annual solar-to-electricity conversion efficiency is over 15% better than other CSP plants.

Because no oil-to-salt heat exchangers are required, the solar field is completely integrated with the energy storage system and there is minimal heat loss. This means that the tanks are less than half the size of competing parabolic trough CSP technologies with the same storage capability yet they provide seven hours of thermal storage.

The cold storage tank of both technologies works at 290°C (554° F). The temperature of the hot storage tank in oil-based CSP plants is 390°C (734° F), a difference between hot and cold tank of 100°. The temperature of the hot storage tank in the Archimede plant is 550°C (1022° F), a difference between hot and cold tank of 260°C. Comparing the Archimede plant with oil-based CSP plants the temperature difference between the two storage tanks is 2.5 times higher.

Salt is clean and one big advantage is that once it has been cooled it can be reused. Oil degrades, is flammable and, as a toxic substance, needs to be disposed of carefully. In addition, molten salt allows the steam turbines used in the CSP process to operate within the standard pressure and temperature regulations at which fossil fuel plants run. This provides the potential for conventional power plants to be integrated easily with CSP plants like Archimede.

Conjugate Heat Transfer Simulation

Unfortunately the advantages of molten salt also present a technical challenge: to maintain the salt's liquid state. Daniele Consoli, Project Engineer in the Engineering and Innovation Division of ENEL, explains, "At 220° C (428° F) salt is frozen. It melts at 240° C (464° F) and in order for it to remain liquid it must be kept at 290° C (554° F). When molten salt acts as the heat transfer fluid circulating in the tubes in which irradiation is concentrated, the pipes must be able to withstand constant heat up to 300° C (572° F) degrees to prevent the salt solidifying and causing an obstruction. An electrical trace system is therefore required to preheat the pipeline and to facilitate the emptying of the circuit which drains the solar collector." Accordingly, the Research Division of ENEL chose to make the pipeline from a stainless steel alloy to withstand extremely high temperatures.

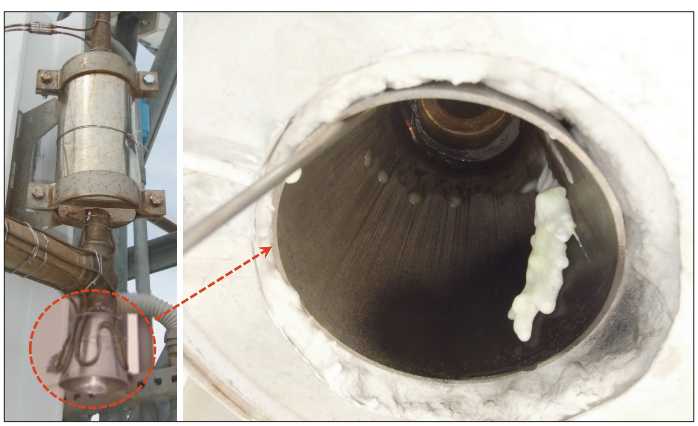

Figure 1. Drainage system and detail of conic shape drain

"This is an experimental power plant and there have been some critical points throughout the project," continues Daniele Consoli. "COMSOL Multiphysics has helped us to solve technical issues as they arose, for example when we needed to analyze temperature and heat loss throughout the drainage circuit and optimize both its geometry and insulation properties." The team created a model of the drain

(Figure 1) within COMSOL Multiphysics and the results (Figure 2) were quickly validated by a physical investigation of thermography (Figure 3) and thermocouple measurements.

"To begin, we undertook two kinds of simulation. Firstly we created a stationary model and used it to determine the level of heating power which needed to be applied by cable to ensure that the temperature in all areas of the drainage system remained above the point at which salt solidifies. We carried out a 3D solid-fluid conjugate heat transfer simulation where both the conic drain part and the surrounding air were modeled. We considered heat transfer by conduction in the former, while both conduction and convection were taken into account in the latter. All the material properties were temperature dependent. We simulated heat loss in the remaining part of the drain by using COMSOL's built-in library of local heat transfer coefficients. Thanks to such coefficients we saved both computational time and resources without affecting the accuracy of the simulation."

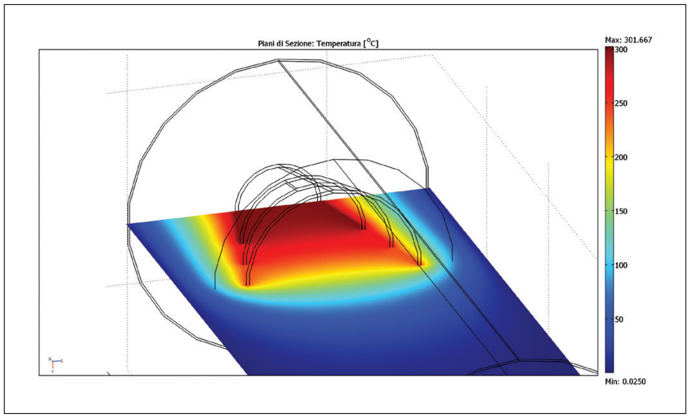

Figure 2. COMSOL simulation of the conic shape drain (the temperature field expressed in °C is shown).

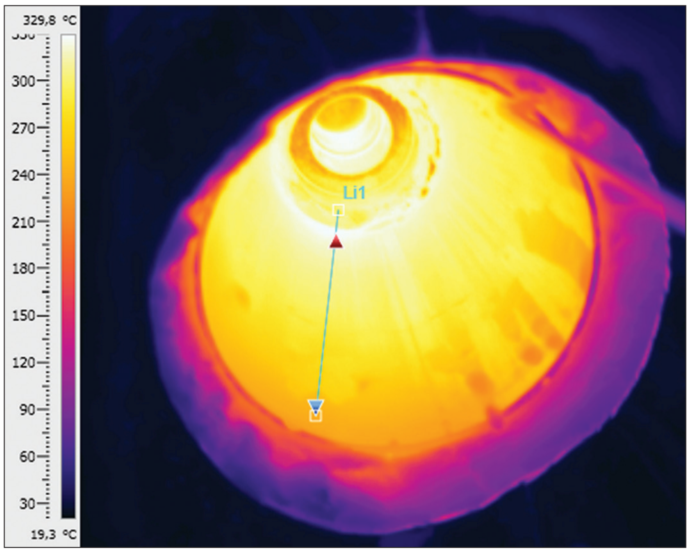

Figure 3. IR Thermography of the conic shape drain.

"Being able to simulate plant operation related to design choices on critical components was extremely important."

The team then created a second, dynamic, model to study the transient heating of the drain and check the time required to achieve the desired temperature.

Another example of COMSOL application in CSP plant analysis has been the development of a model of the storage system to assess how, after validation, it could be optimized for plants of a larger size. This may incorporate several thermal bridges which would have to be assessed in order to avoid the potential for significant and costly thermal power losses. Daniele Consoli explains how heat transfer was modeled, "We considered heat transfer by conduction along the thickness of the wall (steel, insulation, aluminium sheet) and the foundation of the tank. We took both conduction and convection into account for the fluid (molten salt) and convection and radiation for the surrounding air outside the tank."

Reliable Process Operation

Given the over 50 million Euro ENEL total investment in the Archimede project, it was not difficult for Daniele Consoli to propose a business case for COMSOL Multiphysics. "Being able to simulate plant operation related to design choices on critical components was extremely important. In the case of the drainage circuit, simulation may significantly reduce the risk of potential damage to the power plant and the consequent costs in case of failures. COMSOL Multiphysics represented an appropriate tool for those analyses."

From the operating and maintenance point of view the drain represents a single point of failure. "If it failed we would have to stop one branch of the plant from producing energy whilst we undertook a repair operation. Then we would need to follow complex procedures in order to reactivate the affected branch, a process that takes at least 2 working days. All this would result in the loss of tens of man-hours, significant operational income, and above all, clean energy. In addition, being aware of the thermal stresses that the drain and the whole plant are subjected to, we can schedule the preventive maintenance in a more effective way."

According to Daniele Consoli another way to have sized the heating cables would have been via an iterative process based on experience and on monitoring the effectiveness of incremental changes in an empirical way. "With COMSOL we quickly discovered the exact amount of thermal power required and then validated the results directly."

The Archimede project has attracted great interest from utility companies within Europe and around the globe. Daniele Consoli again, "We were building the first power plant in world to use this technology and we needed to get the first plant right and then go on to improve it. There are many potential opportunities for solar thermodynamic technology and the next Parabolic Trough CSP may be much larger. As the technical challenges may also be bigger we will continue to employ COMSOL Multiphysics." ■