



ALGOR FEA HELPS ENGINEERS ENERGIZE SOLAR CELLS

According to the U.S. Department of Energy, photovoltaic power will be competitive in price with traditional sources of electricity within 10 years.¹ Contributing to this trend, Solar Power Industries, Inc. (SPI) of Belle Vernon, Pennsylvania, uses finite element analysis (FEA) software from Pittsburgh-based ALGOR, Inc. as a tool for developing faster, more efficient and less expensive ways to manufacture solar cells.

For example, SPI used ALGOR FEA to analyze the process of casting silicon ingots inside a directional solidification furnace. "These ingots are used to manufacture photovoltaic solar cells," said Chenlei Wang, Ph.D., Senior Engineer with SPI. "ALGOR multiphysics software helped us in optimizing the furnace's hot-zone design, which was the key factor for the project."



Solar Power Industries, Inc. manufactures solar cells at their state-of-the-art, automated facilities in Belle Vernon, Pennsylvania. A rooftop solar array (shown at bottom), which converts sunlight into electricity and feeds directly into the building's main power supply, was installed by SPI at Carnegie Mellon University.

Keeping Pace with Growing Demand

Incorporated in 2003, SPI has continually improved its solar cell production operations to better serve the solar energy industry's rapidly growing markets, particularly in Europe and Asia. "Our current

annual production capacity for processing polycrystalline silicon feedstock into completed solar cells has grown to 40 megawatts," said Wang. "We are focused on becoming a leader in the production of solar cells and we plan on significantly increasing capacity to reach 250 megawatts over the next several years."

SPI's solar cell manufacturing process consists of three main steps:

- 1) *Ingot and wafer production* – High-quality silicon feedstock (containing specific quantities of dopants such as boron in order to alter electrical properties) is melted and solidified inside a directional solidification furnace to cast polycrystalline silicon ingots. The ingots are cut into rectangular blocks with a square cross-section and then the blocks are sawed into thin multicrystalline wafers.
- 2) *Cell production* – The wafers are etched to remove surface damage caused by sawing. The wafers are then processed in a series of steps to produce photovoltaic cells.
- 3) *Module assembly* – Individual cells are connected by soldering to flat wires. Strings of cells are then joined to parallel connector wires and laminated to produce a solar module.

Modules can be installed in a solar energy system to convert captured sunlight into usable electricity. For example, SPI installed a rooftop array of 120 solar panels at a building on the Carnegie Mellon University campus, which feeds directly into the main power supply, providing approximately 10 percent of the building's electricity needs.² That's enough energy to support more than 80 computers while reducing the need for fossil fuel-based electricity. The system also reduces the output of greenhouse gases by more than 31,600 pounds per year.

State Government-Funded Research Project

SPI received funding from the Pennsylvania Energy Development Authority (PEDA) for a research program aimed at expanding the supply of silicon feedstock for producing ingots by the directional solidification technique. Since casting of commercial-size ingots is expensive and time-consuming, there was a need to develop a miniature version of a directional solidification furnace (called a "minicaster") to efficiently cast small ingots for research. "The smaller size of the minicaster would allow for the evaluation of candidate feedstock sources and growth techniques on less material and with faster turnaround times," said Wang. "Thus, the minicaster would allow us to conduct research on variables such as silicon feedstock, doping and solidification cycles."



Chenlei Wang, Ph.D., Senior Engineer, stands in front of SPI's minicaster. The furnace produces silicon ingots that are used for research into making solar cells.

Greg Hildeman, Sc.D., SPI's Vice President of Engineering, stated, "To design, fabricate and test the minicaster, Dr. Wang worked as a member of an SPI project team that included Dr. Daniel Meier and Mr. Vinodh Chandrasekaran." Part of the PEDA funding was used by SPI to purchase ALGOR multiphysics software for analysis of the minicaster design. Wang explained, "The reason we chose ALGOR was due to its cost-effective performance and local service and training program."

Wang attended a one-day training course at ALGOR's headquarters in Pittsburgh, Pennsylvania. "The training was very helpful," he said. "While modeling the minicaster, I used ALGOR's technical support service to discuss particular issues such as mesh generation and transient phase modeling."

Inside the minicaster, silicon feedstock is loaded in a vitreous quartz crucible. Graphite plates surround the crucible – providing mechanical support. Surrounding the crucible is a bank of resistive heaters that uniformly heats the charge. A movable insulation cage serves as the primary means by which the desired cooling rate and directional solidification growth is achieved.

Wang explained, "In order to assess the design of the minicaster 'hot zone' prior to fabricating the components, finite element modeling and analysis was first carried out for the melting phase and then the solidification phase."

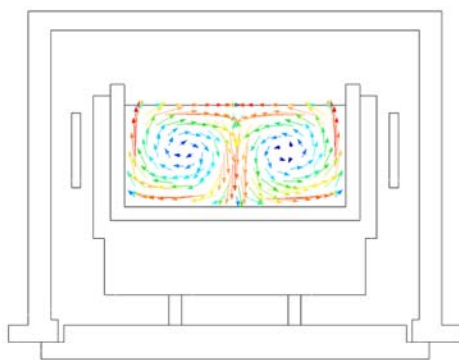
Multiphysics Analysis of the Melting Phase

"We created a 3-D model of the minicaster in Autodesk Inventor," said Wang. "Then, we modeled the cross-sectional geometry in ALGOR."

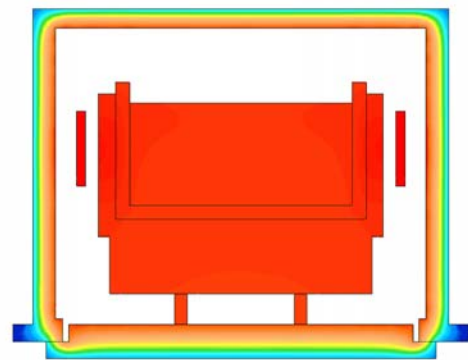
Custom-defined, temperature-dependent orthotropic material properties were specified for the silicon feedstock, quartz crucible, graphite heaters and insulation. Thermal loads were defined for internal heat generation, surface radiation at the outside surfaces and body-to-body radiation between exposed internal surfaces. Fluid velocities were specified for surfaces that surrounded the silicon.

"Natural convection due to buoyancy plays an important role for transport phenomena inside the silicon melt," said Wang. "The strong velocity field inside the silicon melt cannot be neglected. Therefore, we used ALGOR multiphysics analysis to couple the calculation of the silicon melt flow field and temperature field, which accounted for the effect of natural convection."

Wang performed a steady coupled fluid flow and thermal analysis to obtain the convective fluid flow and temperature results for the melting phase.



Minicaster
Melting Phase
Fluid Velocity Vector Plot



Minicaster
Melting Phase
Temperature

Two different types of results are displayed from the ALGOR steady coupled fluid flow and thermal analysis of the melting phase: on the left, fluid velocity vectors within the silicon melt; and, on the right, temperature contours throughout the assembly.

Transient Heat Transfer Analysis of the Solidification Phase

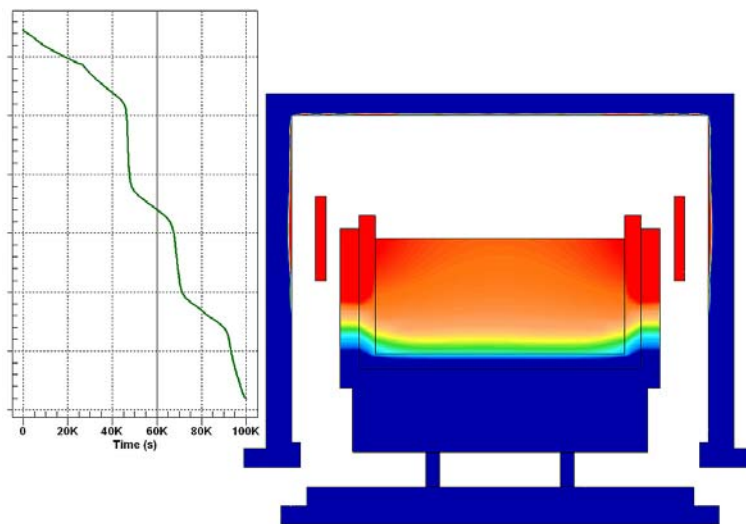
For the solidification phase, a lower internal heat generation value was used to simulate lower temperatures while cooling. ALGOR transient heat transfer analysis results allowed SPI to better understand the minicaster's solidification process.

Upon examining the first silicon ingot produced by the minicaster, SPI noticed some concerns. "Most of the ingot's surface was flat and smooth, but there were some regions at the top of the ingot where the solidification proceeded erratically," explained Wang. "This was thought to be associated with an undesired solidification at the top of the melt, which initiated while solidification was occurring from the bottom upward. Such solidification was predicted by the thermal finite-element model of the growth."



The first silicon ingot produced by the minicaster (left) exhibited regions at the top where solidification proceeded erratically. After the hot zone was modified based on ALGOR analysis results, higher-quality ingots were produced (right).

In order to maximize ingot quality, multiple transient heat transfer analyses of the solidification phase were conducted to determine the best placement and output power for the minicaster's heaters. "By adjusting the heater position and increasing the heater power level by 25 percent, surface solidification was prevented during the growth process," said Wang. "Another effective way to modify the thermal environment was by adjusting the insulation lift distance. The resulting solidification interface was flat and slightly convex to the silicon melt, which is beneficial for high-quality silicon crystal growth."



**Minicaster
Solidification Process
Temperature**

ALGOR transient heat transfer analysis results show the temperature distribution with optimal insulation lift, heater position and heater power level.

Future Plans for ALGOR FEA

"The PEDDA-funded research project was finished in 2006," said Wang, "but research using the minicaster is still ongoing. Additionally, I am using ALGOR to simulate other crystal growth furnaces."

To read a technical white paper about SPI's work, see "'Minicaster' - A Research-scale Directional Solidification Furnace" at:

http://www.algor.com/news_pub/tech_white_papers/minicaster/default.asp.

Dr. Chenlei Wang is a Senior Engineer for Casting Technology. He joined Solar Power Industries in May 2006 and is responsible for optimization of the silicon crystal growth process, thermal system design of DSS furnaces, testing and investigation of new silicon raw material and quality control of wafer production. He is currently conducting studies on silicon crystal growth with different feedstock materials. Dr. Wang earned a Ph.D. degree from the Department of Mechanical Engineering, State University of New York at Stony Brook and has authored 15 journal and conference papers in the area of solar-grade silicon crystal growth. He has more than 8 years of experience in numerical modeling with finite-element, finite-volume and finite-difference methods of heat and mass transfer as well as fluid flow of silicon crystal growth systems for solar applications. For more information about SPI, visit solarpowerindustries.com.

Sources:

1. "Solar History Timeline: The Future" (http://www1.eere.energy.gov/solar/solar_time_future.html), U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Program, January 5, 2006.
2. "Solar Energy Helps Power Campus Facility" (http://www.cmu.edu/cmnews/extra/050718_solar.html), LeeAnn Baronett, *Carnegie Mellon Today*, July 18, 2005.

The names of companies and products mentioned herein may be trademarks or registered trademarks of their respective owners.