Advanced CSP Systems Analysis

Performing Organization: Sandia National Laboratories

Key Technical Contacts: Clifford K. Ho, (505) 844-2384, ckho@sandia.gov
Gregory J. Kolb, (505) 844-1887, gjkolb@sandia.gov
Nathan P. Siegel, (505) 284-2033, npsiege@sandia.gov
Cheryl M. Ghanbari, (505) 845-3426, cghanba@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY2008/FY2009 Budget: $400K for advanced systems analysis (CSP program)
$100K for solid particle receiver modeling (Hydrogen program)

Objectives

- Develop advanced cross-cutting modeling and analysis tools that will aid in the development, validation, and commercialization of CSP components and systems to increase performance and dramatically reduce costs (less than 10¢/kWh by 2015)

Accomplishments

- Performed review of existing codes and software for CSP technologies; identified deficiencies and needs
- Developed and implemented probabilistic methods to quantify uncertainties and sensitivity analyses for assessing system performance and economics of a solar thermal power plant
- Acquired tools and methods to develop integrated models to assess impact of wind, gravity, and thermal loads on optical performance of collector/receiver systems
- Developed and validated model of a solid particle receiver for advanced thermal storage capabilities
- Worked with California Energy Commission (CEC) to develop analyses for glint and glare hazard assessments of solar thermal power plants

Future Directions

- Implement probabilistic modeling into existing tools (e.g., SOLERGY, SAM) and apply to CSP systems to quantify uncertainties and determine which components, processes, and/or parameters need to be prioritized based on impact to performance/economics
- Continue development of integrated models (CAD/fluid/thermal/structural/optical) to understand and optimize system design and performance under normal and off-normal conditions
- Support CEC and companies with modeling and analyses to enable successful certification of CSP systems

1. Introduction

Modeling and analyses are critical to understanding and improving the performance and economics of CSP systems. Because of the complexity of these systems, multiple models of components at various scales are needed. Information from detailed smaller-scale models and tests are often distilled into larger-scale, total-system models (see Figure 1).

This work focuses on the need to develop and integrate rigorous models and analyses of detailed components and processes so that large-scale, total-system models are more accurate and reliable. Probabilistic models are needed to quantify uncertainties and to identify parameters and processes that most impact system performance and cost. In addition, coupled processes such as the impact of wind and gravity loads on optical performance of heliostats or other collectors are needed to better predict performance in normal and off-normal conditions. Finally, models of emerging technologies that can improve system performance (e.g., solid particle receiver for thermal storage) and cross-cutting analyses that will enable certification of CSP systems are described.

2. Technical Approach

A review of existing CSP codes and software was performed to identify gaps and needs in modeling and analysis (Ho, 2008). Based on this review, probabilistic modeling was recommended and demonstrated. In addition, modeling of detailed components and coupled processes was initiated through integrated CAD-based software (Solidworks®), computational fluid dynamics software (FLUENT® and Cosmos FloWorks®), stress analysis (Cosmosworks®), and advanced optical modeling software (ASAP®).

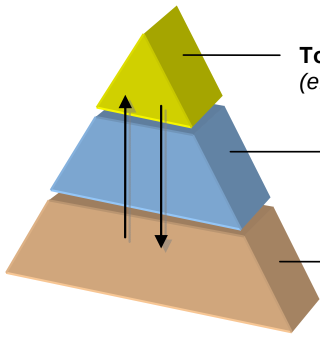

Figure 1. The total-system modeling pyramid.

The results of these codes and models will enable a more thorough characterization of uncertainties and focus research on areas that are most important to enable more reliable total-system model predictions.

3. Results and Accomplishments

3.1 Probabilistic Modeling

Probabilistic models of a hypothetical 100 MW_e power tower were developed to demonstrate the application and benefits of probabilistic methods. In the probabilistic model, selected input variables were treated as uncertain parameters. Each uncertain variable was represented by a distribution of values that was based on data, literature, model results, and/or professional judgment. Multiple runs (realizations) were made using performance, reliability, and cost models. Each run used a set of sampled values from the distribution of input parameters. The result is a distribution of equally probable levelized energy cost (LEC) values.

The distribution of calculated LEC in this example ranged from approximately $0.08/$kWh_e$ to $0.16/$kWh_e$. Figure 2 shows these results as a cumulative distribution function (CDF), or cumulative probability. This plot can be used to predict the probability of the LEC being less (or more) than a particular value, or between two values. For example, in this hypothetical problem, there is approximately a 95% probability that the LEC will be less than ~$0.14/$kWh_e$ and a 5% probability that the LEC will be greater than ~$0.14/$kWh_e$. There is approximately a 0.9 – 0.2 = 0.7 (70%) probability that the LEC will be between $0.10/$kWh_e$ and $0.14/$kWh_e$.

The deterministic model, using expected or "central" values for the uncertain input parameters, predicts an LEC of just over $0.11/$kWh_e$, which happens to be the median (50th percentile) of the probabilistic model. This single value does not provide any indication of the amount of uncertainty in the output (e.g., that there is a 50% probability that the LEC will be greater than $0.11/$kWh_e$ in this hypothetical example). Also, the deterministic LEC value may shift left or right in Figure 2 depending on the nature of the distributions used for the input parameters (e.g., uniform, normal, log-normal).

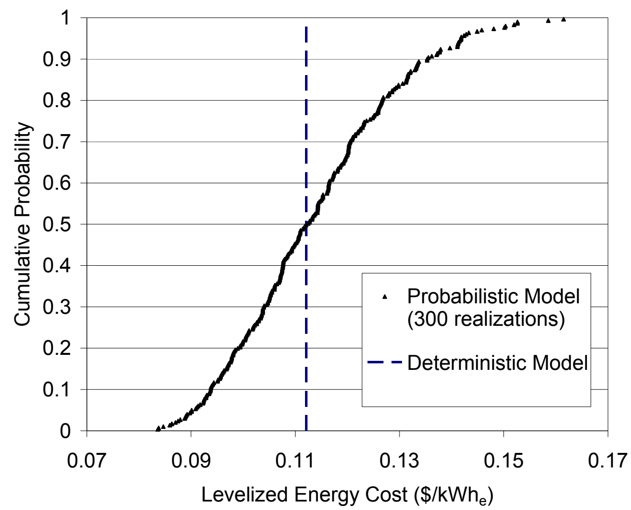

Figure 2. Sample cumulative distribution function (CDF) of levelized energy costs resulting from a probabilistic model.

It should be noted that the number of runs (or realizations) necessary for a random probabilistic (Monte Carlo) simulation increases as the number of uncertain input variables increases. Latin hypercube sampling (LHS) is a method that reduces the number of necessary realizations by ensuring that values are sampled from across the entire input distribution. LHS software has been developed at Sandia National Laboratories that implements this method and allows for correlations among input variables as well.

In addition to the uncertainty analysis described above, a sensitivity analysis was performed to identify those input parameters that most impact the simulated performance metric. Figure 3 shows the results of a stepwise linear regression sensitivity analysis using the multiple realizations shown in Figure 2. The sensitivity analysis shows that the simulated LEC is most sensitive to the heliostat (collector) costs, followed by the O&M costs. Specific processes associated with the performance of the system were also found to be important to the LEC, including reliability of the components, parasitics, receiver absorption, and heliostat performance. Therefore, to reduce costs, further characterization and research efforts could be focused on these components and processes, which were shown to have the most impact on simulated LEC in this hypothetical example.

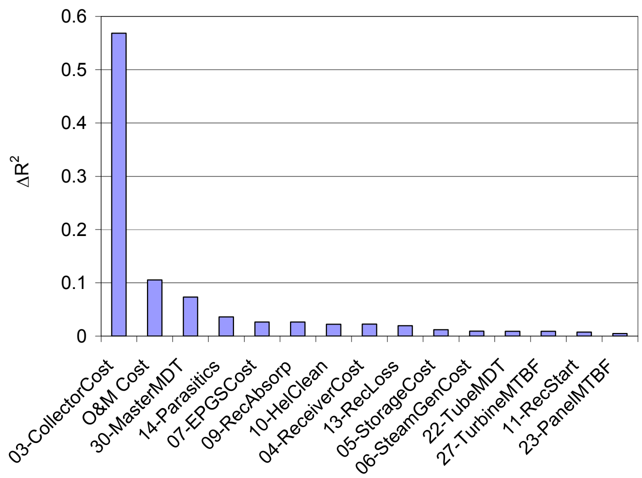

Figure 3. Sensitivity analysis showing relative importance of uncertain input parameters on simulated LEC.

3.2 Coupled-Processes Modeling

Total-system model predictions (e.g., using SAM or SOLERGY) are typically based on "normal" or expected operating conditions. As demonstrated in the previous section, "off-normal" or unexpected conditions that cause uncertainties can significantly impact the predicted results. One example is the impact of wind and gravity loads, which may cause deviations in the optical performance of heliostats. Modeling and understanding the impact of wind and gravity loads on heliostat performance can enable better structural designs to minimize the deviations, or it can provide improved characterization of the uncertainties to improve the reliability of the total-system model predictions.

Models are being developed using integrated codes (Solidworks®, Cosmosworks®, Cosmos FloWorks®, ASAP®) that can predict the coupled effects of wind and gravity loads on optical performance of heliostats and other collectors. Additional work will integrate these simulations with optical simulations to determine the impact on solar flux to the receiver, as well as ways to potentially improve the structural design.

3.3 Solid Particle Receiver Modeling

Advanced solar-based power cycles and thermochemical fuel production processes require thermal energy input with high temperatures in excess of 800°C. Conventional central receiver technologies are capable of reaching a maximum heat input temperature of around 600°C. However, direct absorption receivers using solid particles that fall through a beam of concentrated solar energy for heat absorption and storage have the potential to increase the maximum temperature to around 1,000°C.

Sandia National Laboratories recently designed and tested a prototype solid particle receiver. Tests were performed with concentrated solar power ranging from approximately 1.5 –2.6 MW. Computational fluid dynamics models were developed to simulate the performance of these tests. The simulations included irradiation from the concentrated solar flux, two-band re-radiation and emission within the cavity, discrete-phase particle transport and heat transfer, gas-phase convection, wall conduction, and radiative and convective heat losses. Comparisons between the simulated and measured temperatures of the particles and cavity walls were made, and solar flux parameters were calibrated. Parametric analyses using the calibrated model are being performed to improve the performance of the solid particle receiver. Parameters such as particle-drop position, particle size, particle mass flow rate, and solar flux are being evaluated.

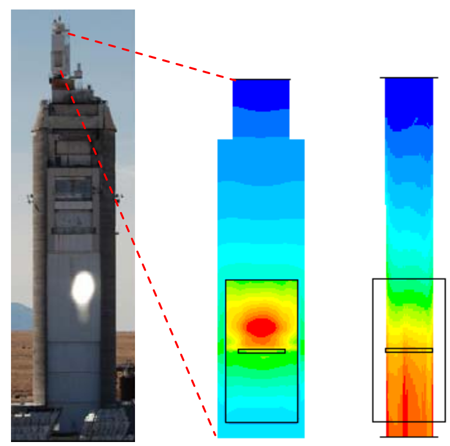

Figure 4. Left: photo of solid particle receiver on top of power tower. Middle: simulated incident solar radiation on the walls of the receiver. Right: simulated temperatures of particles falling through the receiver.

Coupled-process models similar to those used for the solid particle receiver can also be used to rigorously estimate radiant heat transfer and heat losses associated with cavity-type receivers under different scenarios. Results can be used to develop correlations or uncertainty distributions for larger-scale models such as SAM or SOLERGY for power-tower analyses.

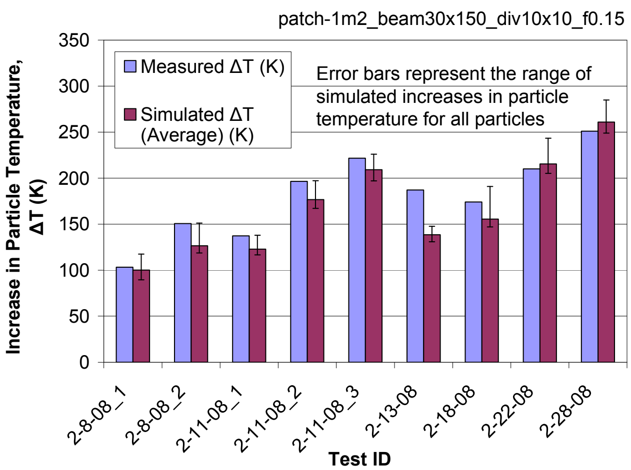

Figure 5. Comparison between measured and simulated particle temperatures for nine on-sun tests (data from Siegel and Kolb, 2008)[1].

3.4 Glint and Glare Analysis

Assessments of the potential hazards of glint and glare from solar thermal power plants are important to ensure public safety. Glint is defined as a momentary flash of light, while glare is defined as a more continuous source of excessive brightness relative to the ambient lighting. Hazards from glint and glare from solar thermal power plants include the potential for eye injury (retinal burn) and distractions. Distractions from glint or glare can also be hazardous to pilots flying overhead or to motorists driving alongside the site.

Applications and certifications for solar thermal power plants often require an assessment of "visual resources" at the site, but these requirements typically focus on aesthetic qualities and standards. Certifications also require an evaluation of general health and safety issues associated with the site, but rigorous and uniform treatment of glint and glare can be lacking, and only the specific system and configuration being permitted are discussed. Models and analyses are being performed to summarize previous research and assessments of glint and glare in each of the primary concentrating solar power technologies: (1) power tower systems, (2) linear concentrator systems (e.g., parabolic troughs), and (3) dish/engine systems. In addition, cross-cutting analyses are being developed that can be used by applicants seeking certification of solar thermal power plants.

4. Planned Activities

The work being performed for advanced CSP systems analysis will enable more reliable total-system model predictions (e.g., using SAM or SOLERGY). Uncertainties in system components and processes will be better characterized, and identification of elements that most significantly impact system performance and cost can be identified. These analyses and models can also be used to optimize design and operation through a better understanding of the impact of detailed coupled processes.

Planned activities for FY09 and beyond include the following:

- Integration of probabilistic methods into total-system models such as SOLERGY or SAM
- Continued development of integrated models to analyze impacts of coupled processes such as wind and gravity loads on optical performance of heliostats
- Parametric analyses of validated solid-particle-receiver model to optimize design for next-generation prototype
- Completion of glint and glare hazard analyses for solar thermal power plants

5. Publications

Ho, C.K., Software and Codes for Analysis of Concentrating Solar Power Technologies, SAND2008-8053, Sandia National Laboratories, Albuquerque, NM.

Ho, C.K., and G.J. Kolb, Probabilistic Modeling of a Solar Thermal Power Plant, submitted to SolarPACES 2009, Berlin, Germany, September 15-18, 2009.

Ho, C.K., and C.M. Ghanbari, Hazard Analyses of Glint and Glare from Solar Thermal Power Plants, submitted to SolarPACES 2009, Berlin, Germany, September 15-18, 2009.

Ho, C.K., and G.J. Kolb, Incorporating Uncertainty into Probabilistic Performance Models of Concentrating Solar Power Plants, submitted to the 2009 ASME 3rd International Conference on Energy Sustainability, San Francisco, CA, July 19-23, 2009.

Ho, C.K., S.S. Khalsa, and N.P. Siegel, Optimizing the Design of a Solid Particle Receiver for Concentrating Solar Power Processes and Storage, submitted to the 2009 ASME 3rd International Conference on Energy Sustainability, San Francisco, CA, July 19-23, 2009.

Acknowledgments

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

---

[1] Siegel, N. and G. Kolb, 2008, Design and on-sun testing of a solid particle receiver prototype, ASME Energy Sustainability 2008, Jacksonville, FL, April 10-14, 2008.