

Description of SAM's CSP User-defined Power Cycle Model

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- Modified the regression methodology in Equations (4) (5), and (6) to use as the design value the calculated design dependent variable at the *table* design value of the independent variables (Y_{des}) instead of 1.0. While we highly recommend that the dependent variables at the table design point are close to 1.0, the model does not enforce this behavior. As such, the revised model accurately captures the relative off-design behavior of a table where the value of at least one dependent variable at the *table* design value is not 1.0.
- Updated the User Interface with a macro for populating sets of independent variables and added calculated variables defining the data table.

Motivation

SAM models parabolic trough, linear Fresnel, and molten salt power tower configurations that employ a heat transfer fluid (HTF) to absorb solar irradiance and deliver it as thermal power to a thermodynamic power cycle that utilizes a separate working fluid (e.g. steam). This type of configuration is known as an “indirect HTF” configuration, as opposed to “direct HTF” configurations wherein the power cycle working fluid also passes through the receiver (e.g. direct steam power tower). SAM’s default indirect HTF power cycle model is a regression model developed from a detailed first-principles basis Rankine cycle model. This basis model calculates cycle performance over the expected cycle operating range by modeling each cycle component at off-design conditions. The model assumes that deviation in cycle performance at off-design conditions is independent of cycle design and only a function of deviation from the user specified design point. This model generally has been a fast, flexible, and accurate tool for most conventional CSP power cycles. However, there are also situations where it is necessary to represent custom Rankine cycle performance or to model next-generation cycle concepts.

Approach

Overview

NREL has developed a user-defined power cycle (UDPC) option for SAM’s indirect HTF technology models to meet this growing demand to model diverse and custom cycles. This option presupposes that the user has a custom power cycle model that can be used to generate cycle performance results over expected operating conditions. The methodology uses a structured design-of-experiments approach to guide and limit the number of custom power cycle simulations required. SAM provides a data table in its User Interface to store the user’s performance data. SAM uses this tabular data to build a power cycle regression model that considers single variable effects and two variable interactions. The following sections explain the user-defined power cycle option in more detail.

Custom Power Cycle Model Requirements

The UDPC requires as independent inputs the HTF temperature ($T_{HTF,hot}$), normalized HTF mass flow rate (\bar{m}), and ambient temperature (T_{amb}). Conceptually, the custom model calculates the outputs in the form of Equation (1), where Y represents any normalized model output (e.g. cycle electric power over design electric power). Because SAM's technology models depend on the relationship between temperatures, mass flow rate, and thermal power to balance mass and energy between component, it is important that the custom cycle model is assuming HTF properties corresponding to the HTF selected in the SAM user interface (UI).

$$Y = f(\bar{m}, T_{HTF}, T_{amb}) \quad (1)$$

The custom model must return calculated normalized (relative to the metric value at the design point value of the independent variables) metrics that define the cycle's performance; at a minimum, SAM requires the thermal power delivered to the cycle from the HTF (\bar{q}_{HTF}) and cycle electric power generated (\bar{W}_{cycle}). Given these values, SAM applies Equation (2) to calculate the HTF cold temperature exiting the power cycle ($T_{HTF,cold}$), where c_p is the HTF specific heat at the average of the hot and cold temperatures. SAM also allows the user to optionally report calculated cooling parasitic load ($\bar{W}_{cooling}$) and cycle water use (\bar{m}_{water}). Because the UDPC model deducts the cooling parasitic load from the cycle electric power (Equation (3)), the user must be sure that these two outputs are defined consistently. Differentiating cooling parasitics from cycle power allows for accurate calculation of cycle heat rejection and helps users understand energy flows in the system.

$$T_{HTF,cold} = T_{HTF,hot} - \frac{\bar{q}_{HTF} * \dot{q}_{HTF,design}}{\bar{m} * \dot{m}_{design} * c_p} \quad (2)$$

$$\dot{W}_{net,calculated} = \bar{W}_{cycle} * \dot{W}_{cycle,design} - \bar{W}_{cooling} * \dot{W}_{cooling,design} \quad (3)$$

Custom Cycle Design Point Performance

SAM's technology models expect the cycle design point HTF hot temperature to match the user-specified solar field design outlet temperature and the normalized HTF mass flow rate to be 1.0. The user selects the design point ambient temperature for the cycle. At these design values of the cycle model independent variable, the technology model expects the normalized outputs to be 1.0. However, SAM does not enforce this behavior. In a technology model simulation where the UDPC data does not return values near 1.0 at the design values of the independent variable, the cycle and plant behavior may not be consistent with design-point metrics like cycle power, solar power, and hours of storage.

Sampling the Custom Power Cycle Model

With a custom cycle model meeting the above requirements, the user must populate SAM's data table with cycle outputs. The goal of the data table is to accurately capture the custom cycle performance over practical ranges for each of the three independent inputs (for example, the normalized HTF mass flow rate may float between 0.3 and 1.1 during an annual simulation). One way to ensure that the table represents the custom

cycle over its expected operating conditions is to require the user to sample a dense mesh of input combinations. For example, if the user determines that 20 values accurately represent the range of possible values for each input, then the user would need to complete 8000 (i.e. 20^3) custom power cycle simulations. For many detailed process simulation software packages, this is a significant computational burden. Moreover, SAM would need to import all the calculated data, and the regression model would need to expansively search through the data to find the correct interpolation region at any given set of inputs.

SAM uses a multi-level design-of-experiments approach to limit the number of simulations required to represent the custom power cycle model by modeling single variable effects and two variable interactions. This approach requires that the user define *low* and *high* level values for each input relative to its design value, designated in Table 1 by – and + superscripts, respectively. The *low* level value should be less than the input's design value (designated by the * superscript) and greater than or equal to the lowest value of the input's practical range. For example, if the practical range of the normalized HTF mass flow rate is from 0.3 and 1.1 and the design value is 1.0, then the *low* level of HTF mass flow rate could be 0.5 or 0.3, but not 0.2. Similarly, the *high* level value should be greater than the input's design value and less than or equal to the highest value of the input's practical range.

This approach requires nine single-variable parametric simulations of the custom cycle model: three for each input. First, the single variable (or *main*) effects are captured by a parametric analysis of the custom power cycle model over the practical range of the respective *main* input with the remaining two inputs at their design values, as shown by Parametric Analyses 2, 5, and 8 in Table 1. Next the *interaction* input for each *main* input is set to its *low* level, and the parametric analyses are rerun, as shown by Parametric Analyses 1, 4, and 7. Finally, the *interaction* inputs are set to their *high* levels, and the process repeated, as shown by Parametric Analyses 3, 6, and 9. In this way, the interaction is captured for each of the three possible combinations of two independent inputs. If the user selects 20 values to cover the practical range for each independent input, for example, then the approach outlined in Table 1 requires only 180 (i.e. 20×9) custom power cycle simulations.

Table 1: Custom Power Cycle Simulations Required to Populate UDPC Data

Parametric Analysis #	Number of Simulations	Custom Model Inputs		
		HTF Hot Temp	HTF Mass Flow Rate	Ambient Temperature
1	$N_{T_{HTF,hot}}$	$T_{HTF,hot}^i$ for $i = 1..N_{T_{HTF,hot}}$	$\overline{\dot{m}}$	T_{amb}^*
2			$\overline{\dot{m}}^*$	
3			$\overline{\dot{m}}^+$	
4	$N_{\dot{m}}$	$T_{HTF,hot}^*$	$\overline{\dot{m}}^{-i}$	T_{amb}^-
5			for $i = 1..N_{\dot{m}}$	T_{amb}^*
6				T_{amb}^+
7	$N_{T_{HTF,amb}}$	$T_{HTF,hot}^-$	$\overline{\dot{m}}^*$	T_{amb}^i for $i = 1..N_{T_{amb}}$
8		$T_{HTF,hot}^*$		
9		$T_{HTF,hot}^+$		

SAM imports results from the parametric analyses in Table 1 as a single data table. Users can enter the simulation data into the table in any order. SAM's UI contains a macro that can populate the table with the corresponding combinations of independent variables when the user defines the low and high levels and design ambient temperature. Then, users can feed this information to their custom power cycle model.

SAM processes the data table in the UI to calculate the design, low, and high values corresponding to the data. This process searches for patterns of independent variable combinations that correspond to the framework in Table 1, and SAM will ignore data that does not fit the framework. Finally, SAM reports the calculated design dependent variables at the *system* design values of the independent variables. That is, SAM uses the user-specified solar field design outlet temperature, a normalized HTF mass flow rate equal to 1.0, and the design ambient temperature calculated from the table.

SAM's Regression Model

SAM calculates off-design cycle performance by using the tabular data in the regression model in Equation (4) where the inputs $T_{HTF,hot}$, $\overline{\dot{m}}$, and T_{amb} , are passed from the other CSP component models.

$$\begin{aligned}
 Y = Y_{des} &+ f_{ME,T_{HTF,hot}}(T_{HTF,hot}) + f_{ME,\overline{\dot{m}}}(\overline{\dot{m}}) + f_{ME,T_{amb}}(T_{amb}) + \\
 &f_{INT,\overline{\dot{m}} \rightarrow T_{HTF,hot}}^{\pm}(T_{HTF,hot}) * \frac{(\overline{\dot{m}} - \overline{\dot{m}}^*)}{(\overline{\dot{m}}^* - \overline{\dot{m}}^{\pm})} + f_{INT,T_{amb} \rightarrow \overline{\dot{m}}}^{\pm}(\overline{\dot{m}}) * \frac{(T_{amb} - T_{amb}^*)}{(T_{amb}^* - T_{amb}^{\pm})} \\
 &+ f_{INT,T_{HTF,hot} \rightarrow T_{amb}}^{\pm}(T_{amb}) * \frac{(T_{HTF,hot} - T_{HTF,hot}^*)}{(T_{HTF,hot}^* - T_{HTF,hot}^{\pm})}
 \end{aligned} \quad (4)$$

where:

- Y_{des} represents the calculated design dependent variable at the *table* design value of the independent variables.

- the $f_{ME,i}(\mathbf{i})$ terms represent the main effect of input i , the difference between the linearly interpolated value from the lookup table at \mathbf{i} and the calculated design value of the dependent variable:

$$f_{ME,i}(\mathbf{i}) = Table_i(\mathbf{i}, \mathbf{j}^*) - Y_{des} \quad (5)$$

- The superscript \pm refers to either the lower or upper level of the *interaction* input, depending on whether the *interaction* input is less or greater than its design value, respectively.
- the $f_{INT,j \rightarrow i}^{\pm}(\mathbf{i})$ terms represent the interaction effect of input j on input i and are calculated two times for each input (one for the upper and one for the lower level of the *interaction* input) from the data table at the beginning of the simulation for each value in the practical range of i using Equation (6). When Equation (4) is applied during the annual CSP system simulation, these terms are calculated by linearly interpolating at \mathbf{i} .

$$f_{INT,j \rightarrow i}^{\pm}(\mathbf{i}) = - \left(Table_i(\mathbf{i}, \mathbf{j}^{\pm}) - Y_{des} - f_{ME,j}(\mathbf{j}^{\pm}) - f_{ME,i}(\mathbf{i}) \right) \quad (6)$$

Equation (4) is solved for each of the four dependent variables, and its normalized output is multiplied to the corresponding design value to calculate the output's dimensional value.

Summary

The following steps define the high-level process to successfully run the user-defined power cycle option in SAM.

1. Develop a custom power cycle model that accepts as inputs the HTF hot temperature, the normalized HTF mass flow rate (with respect to the design point mass flow rate), and the ambient temperature. Ensure that when applying the design point inputs, the calculated outputs match the corresponding values in SAM.
2. For each of the three model inputs:
 - a. Select a practical range covering expected cycle operating conditions over the course of the annual simulation. Create a parametric within this range to accurately capture the cycle response over the operating range (i.e. select the number of values in the range).
 - b. Select *low* and *high* levels required when the input is the *interaction* input.
3. Complete the parametric analyses outlined in Table 1. Optionally, use the macro in the UI to generate sets of independent variables for the parametric analyses.
4. Populate the data table in SAM using the normalized custom cycle results from the parametric analyses. Confirm that calculated table properties displayed in the UI are realistic and match relevant technology model user inputs.
5. Run the SAM simulation.
6. Repeat these steps if you modify SAM inputs that affect the custom model results (e.g. the HTF temperature at design is increased).