

Thermoflow

Comprehensive Thermal Engineering Software

☀ SPOTLIGHT ON SOLAR THERMAL MODELING ☀

Thermoflow Software

Thermoflow Software

Thermoflow provides software for design, simulation, and cost estimation of power, cogeneration, process, and heating plants. Starting in 1987 with its flagship program GT PRO™, Thermoflow's software suite has grown to include seven powerful, yet easy-to-use programs to analyze the spectrum of power generating technologies in use today, and under consideration to meet tomorrow's demanding challenges.

As of 2009, Thermoflow has sold over 7200 program licenses to companies in 75 countries. This proven track record makes Thermoflow's software suite the most widely-used, and well-respected in the power generation industry.

This pamphlet focuses on solar thermal power and heating cycles, a small subset of the full suite's capabilities. You can learn more about the whole suite at thermoflow.com, or by contacting Thermoflow directly.

THERMOFLEX™, together with PEACE™, provides design, simulation and cost estimation for solar thermal power and heating cycles. First released in 1995, THERMOFLEX has been under continuous development ever since. Today, THERMOFLEX is the most well-proven fully-flexible heat balance program available.

PEACE (an acronym for Plant Engineering And Construction Estimator) was introduced as a companion

to GT PRO in 1998. Today, PEACE is integrated into Thermoflow's entire suite. PEACE provides physical equipment specs, capital cost, labor estimates, and estimated installed costs for "engineered" components, including many elements used in solar thermal power plants models.

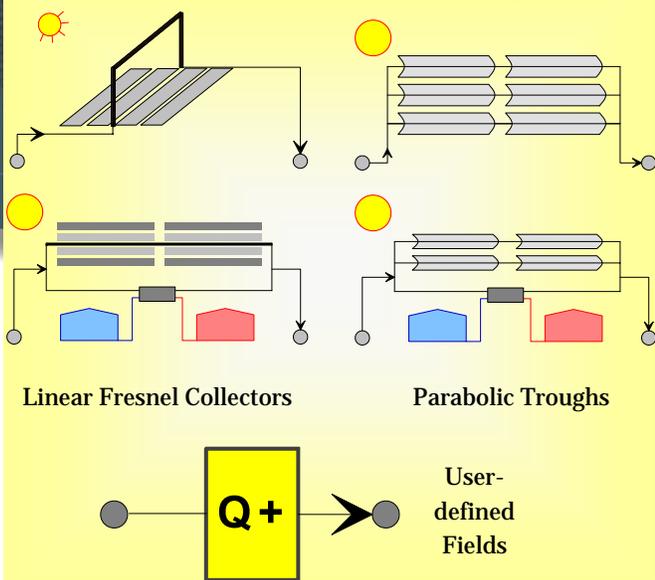
THERMOFLEX & PEACE: Solar Thermal Modeling

These powerful tools are used for heat balance design of thermal power systems, and for simulation of off-design plant performance. THERMOFLEX is flexible. It provides the user full freedom to construct flowsheets using component models available in its toolbox. THERMOFLEX has all the components needed to model complete power plants of virtually every type, or to model only a small subsystem such as a pump and pipe.

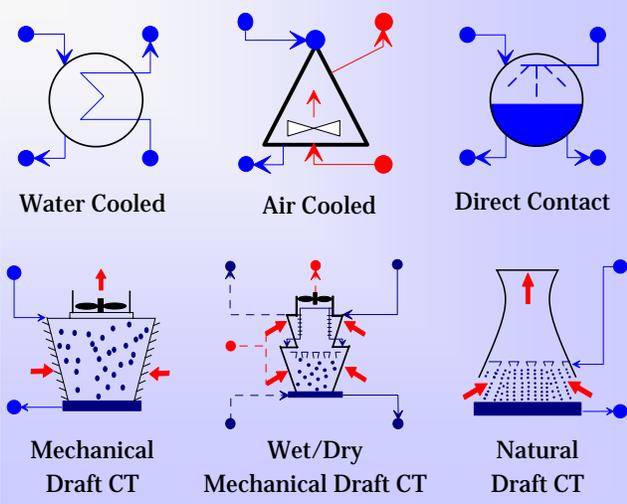
THERMOFLEX Toolkit—Component Models

The icon toolkit includes all the component models and fluid properties needed to build solar thermal power plant models. The model boundary can be all-inclusive; from solar irradiance input to electric delivery on the high-voltage side of step-up transformers. Alternatively, the model can include only a steam turbine and its feedwater heating train, or anything in between.

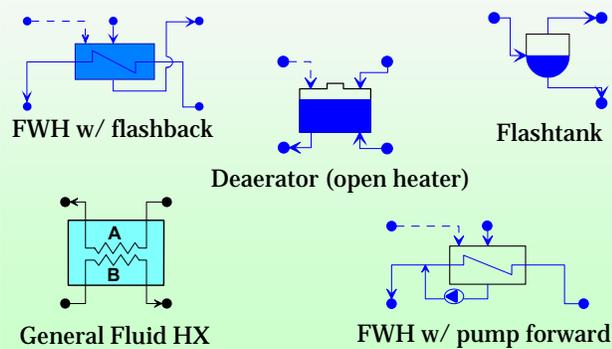
Solar Fields & Solar Fields with Storage



Condensers & Cooling Towers



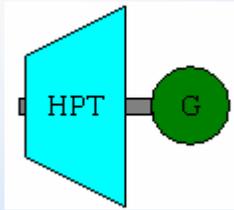
Feedwater Heater Trains—shell & tube LP & HP heaters, deaerators, flashtanks, general-purpose & general fluid heat exchangers



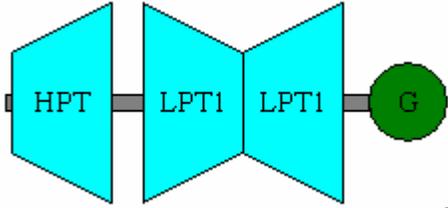
These two pages show only a small subset of the full selection of THERMOFLEX / PEACE model icons - those typically used in solar thermal power plants. As of 2009, THERMOFLEX / PEACE collectively include over one hundred and seventy-five (> 175) different icons. THERMOFLEX includes built-in properties for seven (7) fluid types representing hundreds of specific fluids used in power and process applications.

Solar Thermal Toolbox

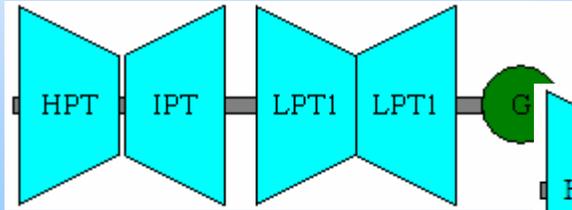
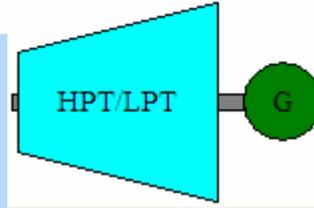
Steam Turbines



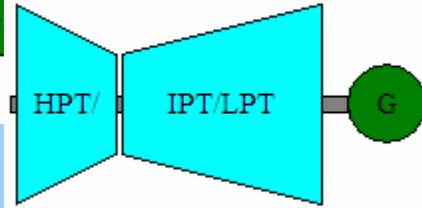
Back Pressure



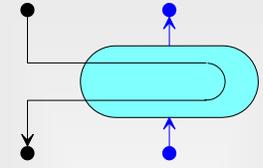
Condensing, Non-Reheat
(single & multi-casing)



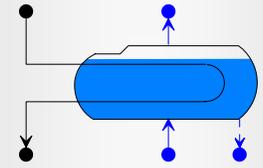
Condensing Reheat
(single & multi-casing)



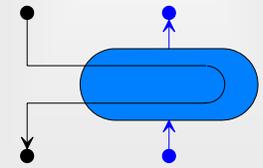
Solar Boilers



Shell & Tube Superheater



Shell & Tube Evaporator

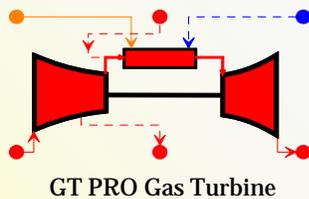
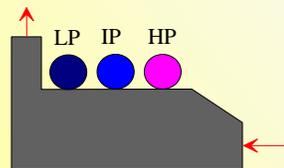


Shell & Tube Economizer

Fluids—seven types with built-in properties to represent hundreds of specific fluids

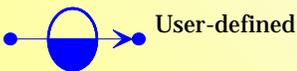
- Water: subcooled, saturated, superheated, & supercritical
- Dry & humid air, combustion products, pure gases such as N₂, CO₂, etc.
- Brine: seawater & brackish water
- Refrigerants: subcooled to supercritical
- Ammonia/Water mixtures
- Heat Transfer Fluids: DOW, Solutia, Paratherm, Duratherm Molten Salt, user-defined, etc.
- Fuels: solid, liquid, gaseous

Gas Turbines & Boilers—Supplemental steam, backup heat input, parallel heating sys-

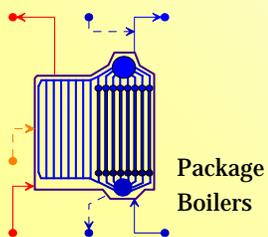


GT PRO Gas Turbine

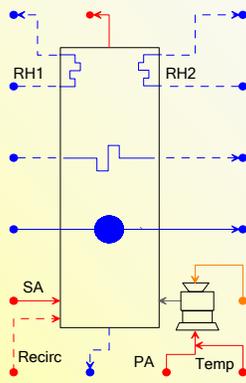
Heat Recovery Steam Generators (HRSG)



User-defined

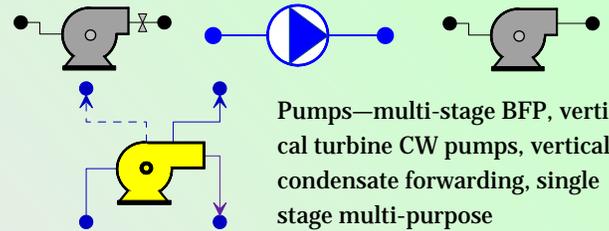


Package Boilers



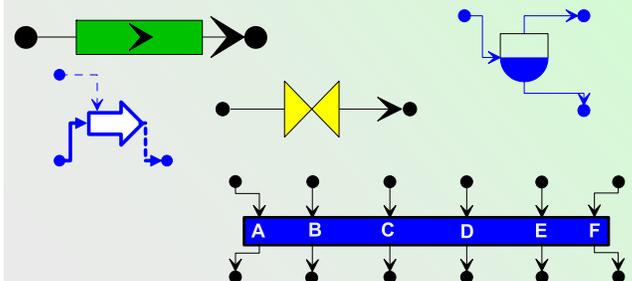
Fired Utility Boilers—
coal, oil, gas

Pumps, Pipes, Headers, Valves, Processes—Network fluid flow modeling



Pumps—multi-stage BFP, vertical turbine CW pumps, vertical condensate forwarding, single stage multi-purpose

Piping systems—physical models with straight runs, headers, fittings, valves, branches, elevation changes, etc.



Solar Field Component

Solar Field Model Options

In solar thermal plants, the solar field supplies some or all of the heat needed by the cycle. The field may deliver hot thermal oil, hot water, saturated steam, or superheated steam.

THERMOFLEX has a completely user-defined solar field where the user directly specifies solar field heat input to the working fluid used in the cycle. In this case, no detailed field modeling is done by THERMOFLEX, rather the user's specified field performance is applied directly. This simple approach makes including manufacturer-specified performance quick and easy.

THERMOFLEX also allows the user to model the solar field's thermal-hydraulic-optical performance directly, in detail. At design, THER-

MOFLEX computes number and length of each collector row, the total solar field size, fluid pressure drop, land use requirements and estimated field cost based, on desired field performance. At off-design the solar field model estimates field heating capacity and fluid-side pressure drop for given solar irradiance and field operating conditions.

The THERMOFLEX solar field model is a general line collector model with options to pick specific parabolic trough and linear Fresnel collector configurations, and ability to specify user-defined collector characteristics.

Design Point

The **Main Inputs** menu for design calculations is shown here. The **Collector Hardware & Charac-**

teristics menu is shown at the top of the next page. These two menus allow the user to specify the desired field thermal-hydraulic performance and the physical and optical characteristics of the collector used. Default values are supplied for all inputs, and the user can always adjust the inputs to suit their needs.

At design, THERMOFLEX uses these inputs to compute the field's thermal-hydraulic performance and estimate the collector size and land requirements.

The solar field consists of a number of flowpaths connecting cold supply header to the hot return header. Each flowpath spans one or more collector rows. Large trough fields typically use two collector rows per flowpath so the hot and cold headers are at the same end of the row banks.

Some linear Fresnel collectors, especially with direct steam generation use one flowpath per collector row so cold fluid enters at one end, and steam exits to a steam drum at the opposite end.

Smaller roof-top heating collectors often have many collector rows per flowpath to accommodate the desired temperature rise in a limited footprint.

Solar Field[1] Engineering Design

ED Main Inputs Irradiance Collector Hardware + Characteristic Flow Path Hardware

Desired fluid massflow 410 kg/s

Desired exit temperature 391 C

Design point collector nominal optical efficiency 70 %

Desired massflux in receiver tubes 2500 kg/m²-s

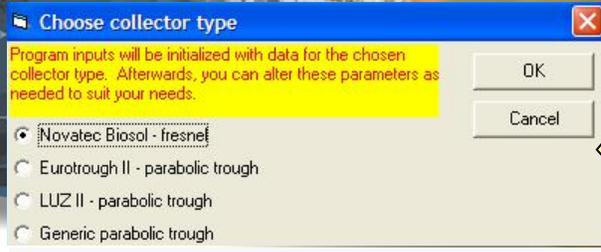
Maximum pressure drop 75 %

Flow Priority
 Strong
 Weak

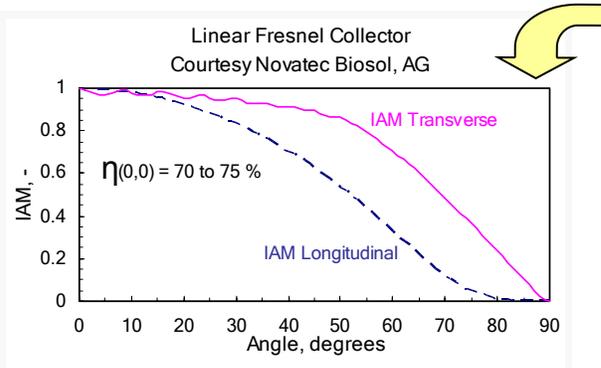
Pressure Drop Calculation
 Use hardware-determined pressure drop
 Use defined performance

Main design-point model inputs. These are desired flowrate, exit temperature, pressure drop, tube velocity (mass flux), and optical efficiency for normal ray strikes. All inputs have default settings that are easily reset as needed. The field model or the heat consumer can ultimately determine fluid flowrate partly based on the 'flow priority' setting.

Design Point Model Inputs



Collector library allows selection of specific collector cross sections and optical properties. The built-in data can be adjusted by the user as needed.



Incident Angle Modifiers (IAM) factors adjust nominal optical efficiency to account for non-incident ray strikes. IAM data may be edited to reflect the specific characteristics of any line collector. The data is typically generated by collector manufacturer using ray-tracing programs. This is key to determining how much irradiance is incident on the receiver, which ultimately affects field effi-

| Angle Degrees | IAM Longitudinal | IAM Transverse |
|---------------|------------------|----------------|
| 0 | 1 | 1 |
| 1 | 0.999 | 0.994 |
| 2 | 0.998 | 0.983 |
| 3 | 0.997 | 0.973 |
| 4 | 0.995 | 0.971 |
| 5 | 0.993 | 0.971 |
| 6 | 0.991 | 0.977 |
| 7 | 0.988 | 0.988 |
| 8 | 0.985 | 0.996 |
| 9 | 0.982 | 0.992 |
| 10 | 0.978 | 0.98 |
| 11 | 0.974 | 0.97 |
| 12 | 0.97 | 0.967 |
| 13 | 0.965 | 0.965 |
| 14 | 0.96 | 0.97 |
| 15 | 0.955 | 0.981 |
| 16 | 0.949 | 0.986 |
| 17 | 0.943 | 0.979 |
| 18 | 0.936 | 0.965 |
| 19 | 0.929 | 0.958 |
| 20 | 0.922 | 0.956 |
| 21 | 0.915 | 0.955 |
| 22 | 0.907 | 0.963 |
| 23 | 0.899 | 0.97 |
| 24 | 0.89 | 0.967 |
| 25 | 0.88 | 0.952 |

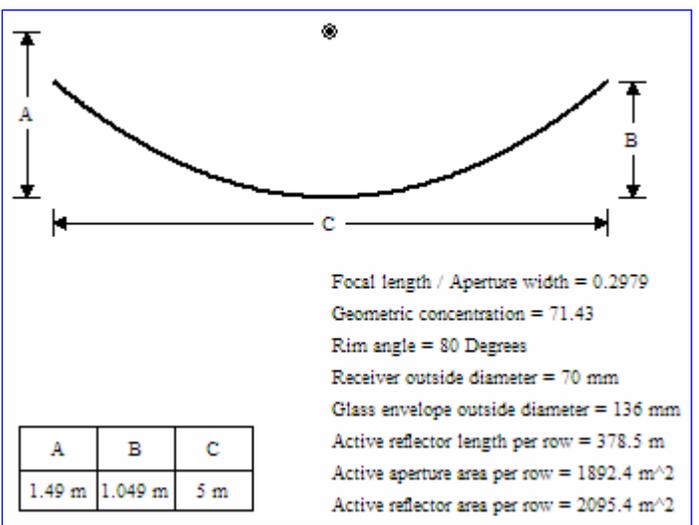
- 1. Number of IAM data points: 91
- 2. Line collector type: 0=parabolic trough, 1=linear fresnel: 1
- 3. Receiver tube outside diameter: 70 mm
- 4. Receiver tube wall thickness: 4.191 mm
- 5. Aperture width (sum of primary reflector widths): 12 m
- 6. Aperture width / Collector unit width (Fresnel only): 0.7246
- 7. Collector unit width (for information Fresnel only): 16.56 m
- 8. Collector focal length: 7.4 m
- 9. Number collector rows per flow path: 2
- 10. Number collector row banks: 1
- 11. Active reflector length as percent of total length: 95 %
- 12. Collector unit row pitch / collector unit width: 1.242
- 13. Reflector cleanliness factor: 0.95
- 14. Row (tracking axis) rotation from due North: 0 Degrees
- 15. Row (tracking axis) tilt from horizontal: 0 Degrees
- 16. Coefficient A1 in heat loss per unit length equation: 1 W/m-C
- 17. Coefficient A2 in heat loss per unit length equation: 1.963E-8 W/m-K^4
- 18. Overall heat loss correction factor: 1
- 19. Number of computational segments along receiver: 10

This menu is used to specify collector cross-section, receiver dimensions and heat transfer characteristics, and desired field arrangement. This data can be selected from a library of built-in collectors, and/or be edited directly.

The **Flow Path Hardware** menu (below) is used to specify hydraulic parameters affecting the pressure drop from cold header to hot header. The fittings specified here together with the straight run of receiver

tube with its specified roughness are used to compute an equivalent length of straight piping. The pressure drop is computed using that

| | |
|---|------------|
| 1. Receiver tube internal roughness | 0.00152 mm |
| 2. Number of additional velocity heads of pressure loss | 2 |
| 3. Number short 90 deg. elbows | 4 |
| 4. Number long 90 deg. elbows | 0 |
| 5. Number sweeping 90 deg. elbows | 0 |
| 6. Number short 45/60 deg. elbows | 0 |
| 7. Number long 45/60 deg. elbows | 0 |
| 8. Number globe valves | 0 |
| 9. Number gate valves | 2 |
| 10. Number drains | 0 |
| 11. Number expansion joints | 0 |



Collector cross section data, as set by user, or automatically by THERMOFLEX, is displayed as one of the graphic output reports.

Receiver tube roughness, and number/type of fittings installed in each flow-path can be set automatically, or by user input. These parameters impact the computed field pressure drop, and hence pump size and power requirements.

Solar Resource

Solar Resource

Site irradiance levels and the relative sun-collector position are two key parameters for the solar plant designer. Once a system is designed (sized), its heating ability at different times of day, on different days of the year is heavily dependent on the site's solar characteristics.

THERMOFLEX provides four ways to input irradiance and relative sun-collector positioning. Each method is designed to make it easy to use assumptions, actual measurements, or data from statistical analysis, such as TMY3 data.

1. Estimated from Site Data

This method is most useful for up-front scoping studies where the

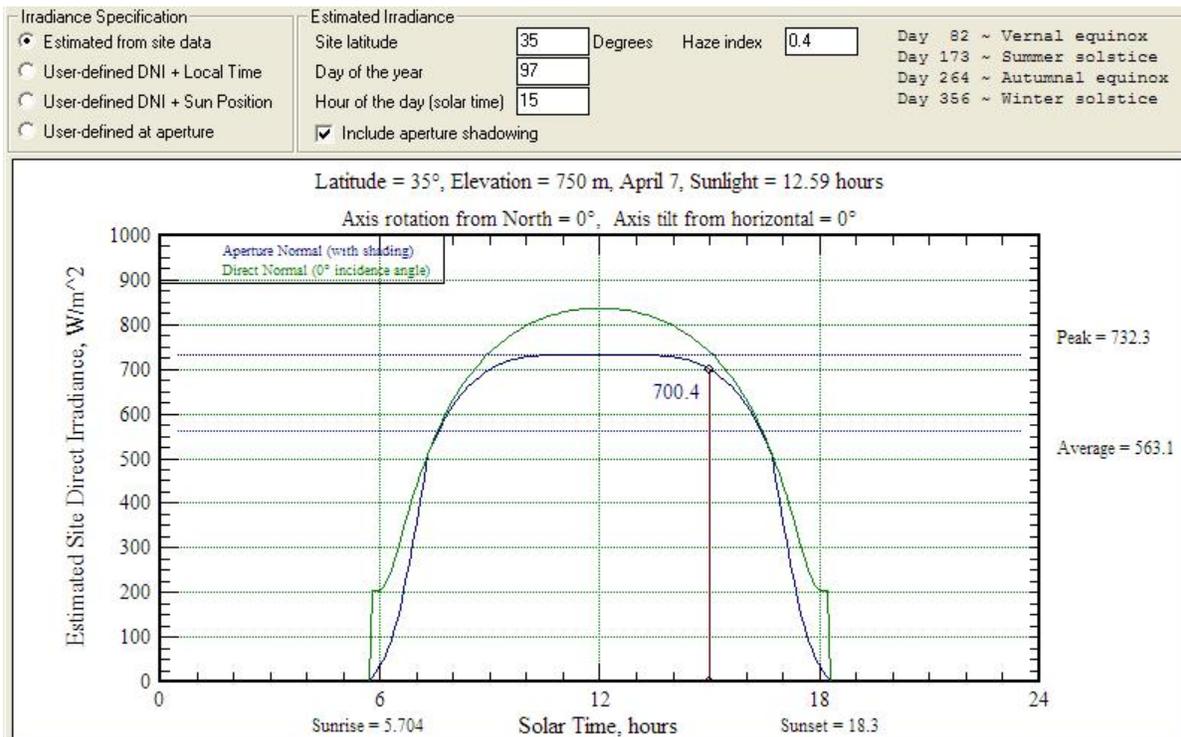
plant designer has limited access to detailed site-specific irradiance data, yet still wants to compute a solar model. It's a great way to "get started" or to compare relative site performance.

THERMOFLEX estimates the DNI and relative sun-collector angles using a model of relative sun-earth positioning as a function of time of day and day of year. Ground-based irradiance is computed using an estimate of atmospheric transmissivity. This atmospheric representation is most applicable for sites with a large number of sunny days per year, those typically most desirable for solar thermal plant siting.

This method makes it easy to pick a

time of day, and a day of year for a specified site, and rely on the program to compute irradiance and solar angles.

The input menu for this method is shown below. The **Estimated Irradiance** panel along the top includes the solar-specific inputs needed to estimate irradiance. Site altitude is set elsewhere. The daily variation in DNI and ANI (Aperture Normal Irradiance) are shown as a function of solar time as the green and blue lines, respectively. The graph title shows a summary of the conditions used to estimate the irradiance together with the length of the solar day. Daily peak ANI and daily average ANI values are shown to the right.



Plot shows estimated variation in DNI and ANI throughout the day. Site-specific data and day of year used in the estimate shown above the plot. Daily peak ANI and daily average ANI values are shown to the right.

Irradiance and Solar Angles

2. User-defined DNI & Local Time

More detailed plant design and simulation often uses irradiance data measured from ground or satellite. This data is available from a number of sources. In the US, data for hundreds of sites is available in TMY3 datasets available from National Renewable Energy Laboratory (NREL). TMY3 data statistically represent conditions at a specific site by analyzing measurements made over decades. Data sources are available for other locations worldwide, some for free and others on a commercial basis. Regardless of the source, the solar data is characterized by site longitude, latitude, altitude, local time, day of year, and irradiance (DNI, diffuse, total).

THERMOFLEX includes this method of solar data input to facilitate use of TMY3 (and similar) data sets. The **Site location and current time** panel shown on the input menu below lists the input parameters needed. THERMOFLEX computes the solar time from this data using an equation of time. The relative sun-collector positioning is used to compute azimuth and zenith angles associated with the specified day and time.

| | | |
|--|--------|------------------|
| Site location and current time | | |
| Latitude (>0=North) | 34.63 | Degrees |
| Longitude (>0=East of Greenwich) | -118.1 | Degrees |
| Standard time zone (>0=East of Greenwich) | -8 | hours |
| Day of the year | 82 | (March 23) |
| Local standard time (24 hour clock) | 12 | hours |
| Direct normal irradiance (DNI) | 900 | W/m ² |
| <input checked="" type="checkbox"/> Include aperture shadowing | | |

3. User-defined DNI & Solar Angles

This method is used to directly specify DNI and location of the sun in the sky. THERMOFLEX computes Aperture Normal Irradiance (ANI) from this data using inputs for collector orientation on the earth (N-S, E-W, or other) and tilt from horizontal.

This method is used to specify "typical" irradiance condition for collector design, or when scanning through a range of conditions for off-design simulation.

| | | |
|--|-----|------------------|
| User-defined Direct Normal Irradiance | | |
| Direct normal irradiance (DNI) | 900 | W/m ² |
| Solar zenith angle | 60 | Degrees |
| Solar azimuth angle | 180 | Degrees |
| <input checked="" type="checkbox"/> Include aperture shadowing | | |

4. User-defined ANI

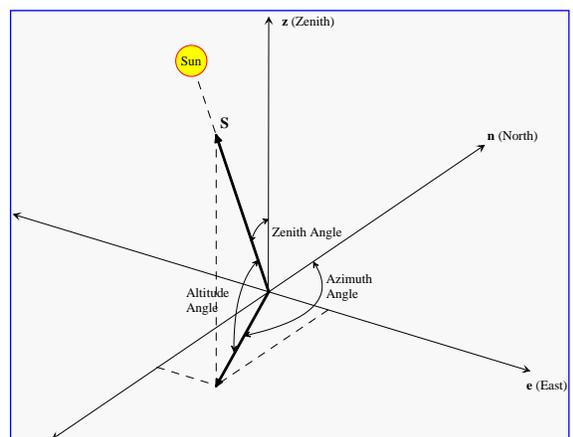
This method is used to directly specify Aperture Normal Irradiance (ANI), that is how much beam irradiance falls normal to the collector aperture. As such, it has a single input value. In this case, THERMOFLEX simply applies this value and ignores collector orientation, solar angles, and other inputs that would be used to ultimately compute this quantity.

| | |
|---|------------------------|
| User-defined Direct Irradiance Normal to Aperture | |
| Aperture normal direct irradiance | 741.6 W/m ² |

This approach requires the least amount of input to THERMOFLEX but usually requires the largest amount of independent calculation outside THERMOFLEX to determine this input value.

Solar Angles

The diagram below shows the definition of solar angles relative to collector midpoint. The collector is not shown, but may be located with primary axis along N-S, E-W, or anywhere in between. Large collectors are typically installed with zero tilt, but the model allows specification of tilt away from the horizontal if needed.



Kramer Junction SEGS VI

Model Overview

The overall heat balance result from a THERMOFLEX model of the Kramer Junction SEGS VI plant is shown below. The well-known facility is a single reheat indirectly heated Rankine cycle with six feedwater heaters. The solar field heats Therminol VP-1 which flows through the solar boiler to make and reheat steam. The steam turbine exhausts to a water cooled condenser serviced by a wet cooling tower.

The model is a complete representation of the entire facility including solar field, solar boiler elements, steam turbine, feedwater heater train, condenser, cooling tower, and associated balance of plant.

For a given model run, the minimum required inputs are (1) Ambient conditions, and (2) Solar irradiance data. The program computes gross

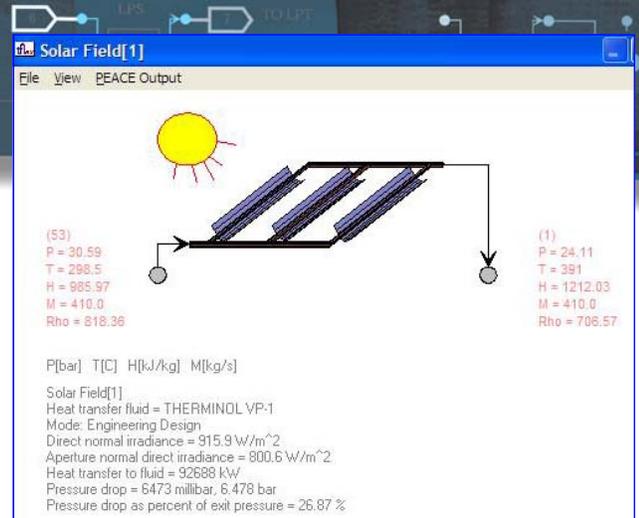
power, net power, auxiliary electric loads, as well as flow, pressure, temperature, and enthalpy throughout the cycle.

The result below is for the 100% solar loading case at design ambient conditions. The plant model produces 35 MW gross electric power, consumes 2.6 MW of auxiliary power, and produces 32.4 MW net power. In the diagram only key state data are displayed for clarity. However, the user can display the state data at every node, and each icon includes a series of text and graphic output reports for each run.

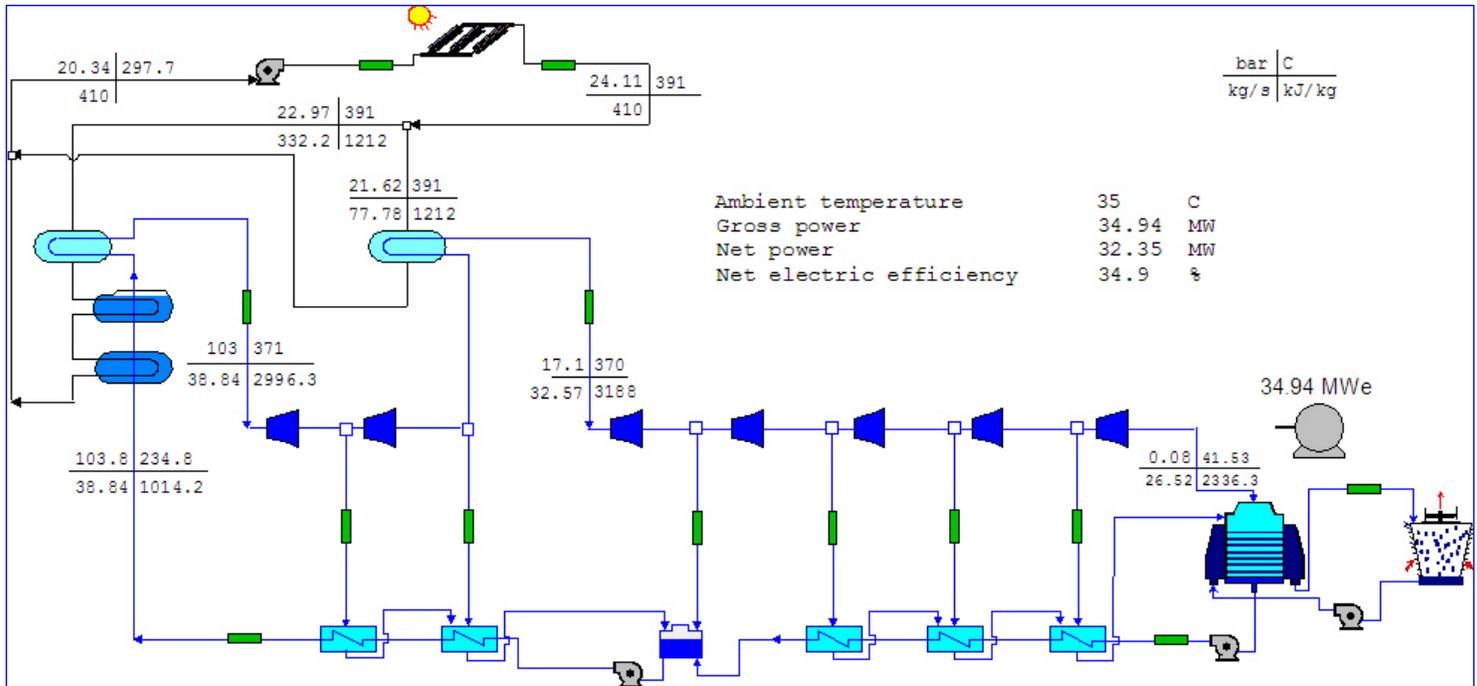
Model predictions match design point data to a high level of fidelity.

Summary Report

Summary results for each component are available by double-clicking



an icon from the overall heat balance view. The display above is the summary display for the solar field. THERMOFLEX includes a library of heat transfer fluids that are commonly used in solar applications. The fluid library includes thermal and physical fluid properties used in pressure drop and heat transfer calculations. In this model Therminol VP-1 circulates within the field and the solar boiler. The solar field diagram shows the state of the Therminol (pink fluid) entering the field on



Overall design point heat balance result from a THERMOFLEX model of the Kramer Junction SEGS VI plant.

Select Model Results & Output Reports

the left, and the field delivery condition and returns to headers in between row banks. Major

A performance summary is shown in blue in the lower left corner. In this model, DNI is 916 W/m², total heat transferred to fluid in the field is 92.7 MW, and the fluid pressure drop from receiver inlet to exit is 6.5 bar, or about 27% of exit pressure.

Detailed Reports

A series of detailed text and graphic reports are presented to describe the computed heat balance, the physical equipment description, and for PEACE components, estimated equipment and installation costs.

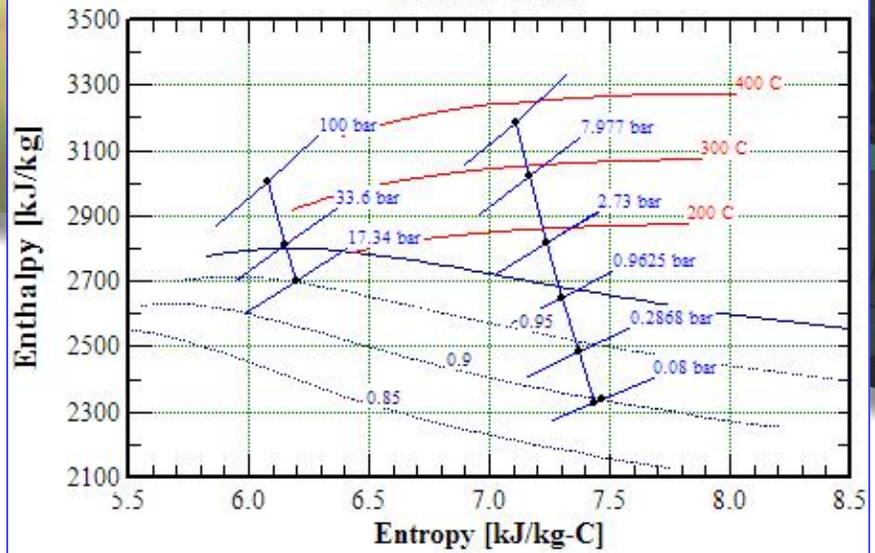
The field size and layout report is displayed below. The bird's-eye view shows the collector rows are oriented North-South. Fifty (50) U-shaped flowpaths are arranged in one hundred (100) collector rows in two row banks. Fluid enters from

and returns to headers in between row banks. Major dimensions are listed along with total field aperture and required land area.

Steam Turbine

THERMOFLEX output reports include text and graphics to describe steam turbine performance, configuration, and cost. Reports include detailed heat balance results in and around the turbine, section efficiencies, turbine casing configuration, leakage schematics, estimated turbine generator size, weight, capital cost, and installation labor.

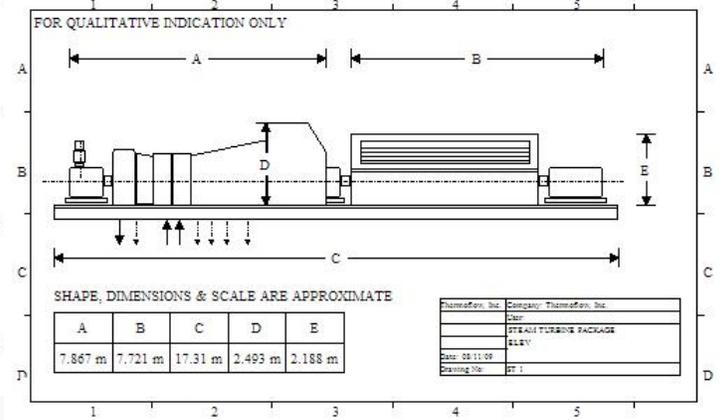
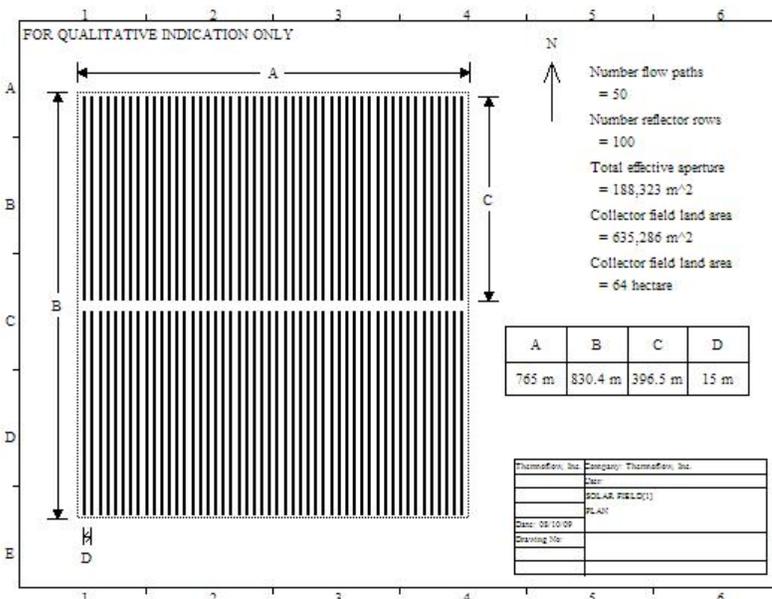
Steam Turbine Expansion Path
Mollier Chart



top right corner above. Extraction pressures for feedwater heaters are shown along the path which consist of an HP section and an IP/LP section with steam reheat in between. Steam exhausts at 80 mbar with a quality of about 90%.

PEACE cost and installation estimates are based on equipment size, weight, and configuration details. A series of reports present this data. The estimated elevation view for the steam turbine is shown below along with a summary of overall dimensions for the turbine and its generator. The steam turbine design model is entirely dynamic, so any changes to design parameters are reflected in these reports, and in the cost and installation labor estimates.

The steam turbine expansion path, Mollier diagram, is shown in the



Solar field bird's-eye view output graphic showing field arrangement and computed land area, aperture area, flowpaths, etc.

Solar Power with Thermal Storage

The Storage Issue

On “good” days, in “sunny” locations, pure solar plants (see preceding pages) produce electricity for seven to thirteen hours of the day. As the sun rises, sets, and is blocked by clouds, the energy capture rate changes; sometimes very rapidly. The steam power plant’s electricity output follows solar capture rate up to a point, but cannot always follow without tripping off-line. In these situations, the solar field must “dump” energy, or defocus to prevent overheating the fluid and field components.

During startup, or following a trip, the solar field and power plant are restarted, and resynched to the grid. This process takes time, and is not always possible given the time of day, or prevailing and expected

weather conditions.

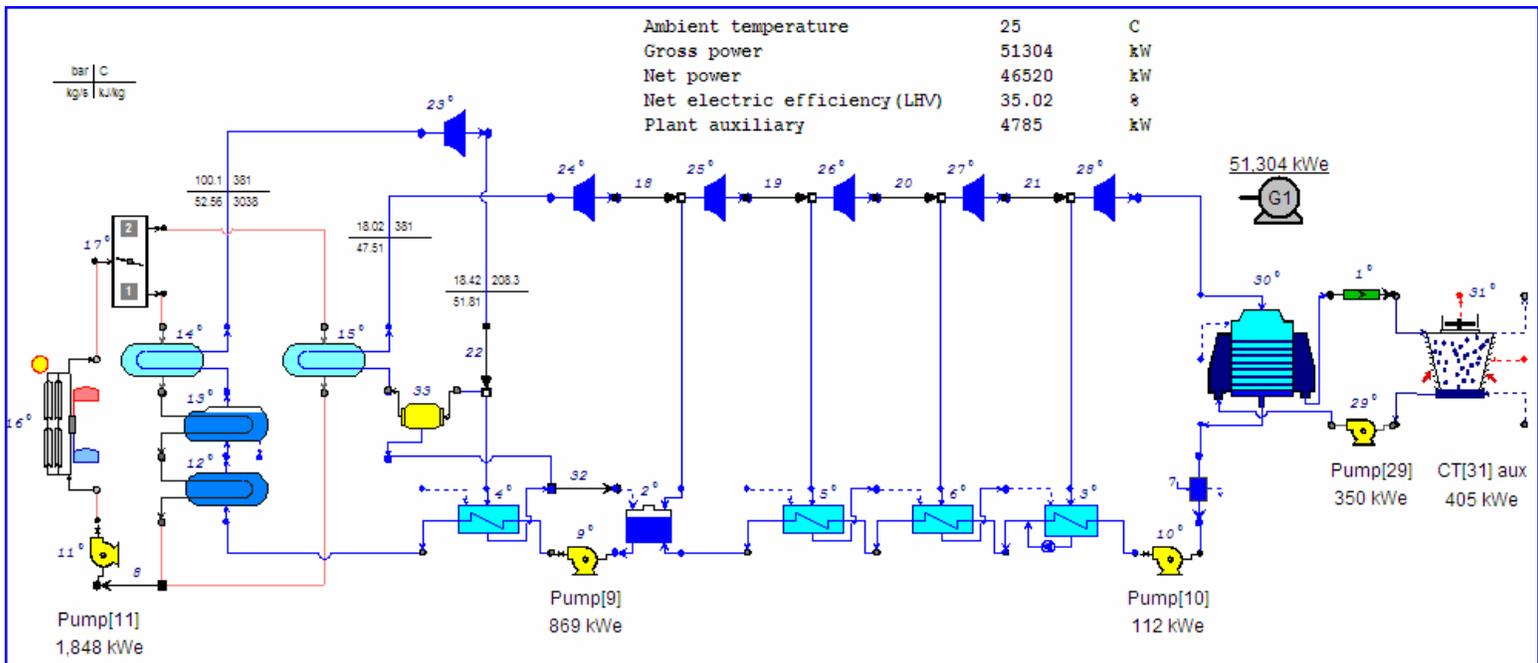
One way to mitigate some problems associated with varying solar availability is to include a thermal storage system to store heat captured by the solar field. The storage system decouples the solar field’s ability to capture heat from the power plant’s demand for heat to achieve a desired power production level. This capacitance effect is useful to ride out transients, and for time-shifting the power production relative to the sun. Storage systems potentially help plants dispatch power in a more predictable and reliable fashion. So, rather than producing a continuously variable power level throughout the day, a plant can deliver a fixed baseload level for a more predictable period. Or, a plant could be dispatched to meet morning and

evening peak demands experienced by many utilities.

Storage Systems

Various types of thermal storage systems have been tried in pilot projects and in commercial power plants. A number of advanced and novel concepts are currently the focus of research efforts. The basic forms of storage are (1) direct oil storage, (2) indirect storage using a second liquid such as salt, (3) indirect using a solid such as concrete, and (4) indirect using a phase change material to capitalize on relatively high apparent heat capacity from melting and freezing suitable materials.

Early storage projects used direct oil storage. Such a system was implemented for a period of time at



Andasol 1 Power Plant

Kramer Junction, but is no longer operational. In this system, some thermal oil from the field is diverted to insulated storage tanks instead of used to make steam. When the heat is needed later on, hot oil is pumped from the storage tanks to the solar boiler where it is used to make steam. This system increases the amount of thermal oil onsite,

which is problematic for permitting reasons, and economic reasons because thermal oils are relatively expensive.

Currently, commercial-scale solar thermal storage is being designed and built using indirect storage. The storage medium is molten salt, not thermal oil. Molten salts are advantageous because they have high volumetric heat capacity, can be stored in atmospheric tanks because of salt's low vapor pressure, and are relatively inexpensive.

Two-tank Molten Salt

The Andasol plants located in Granada Spain, and other similar facilities, use a two-tank molten salt storage system. The system is comprised of separate "hot" and "cold" insulated storage tanks of roughly

equal volume. The schematic above shows such a system operating in charging mode.

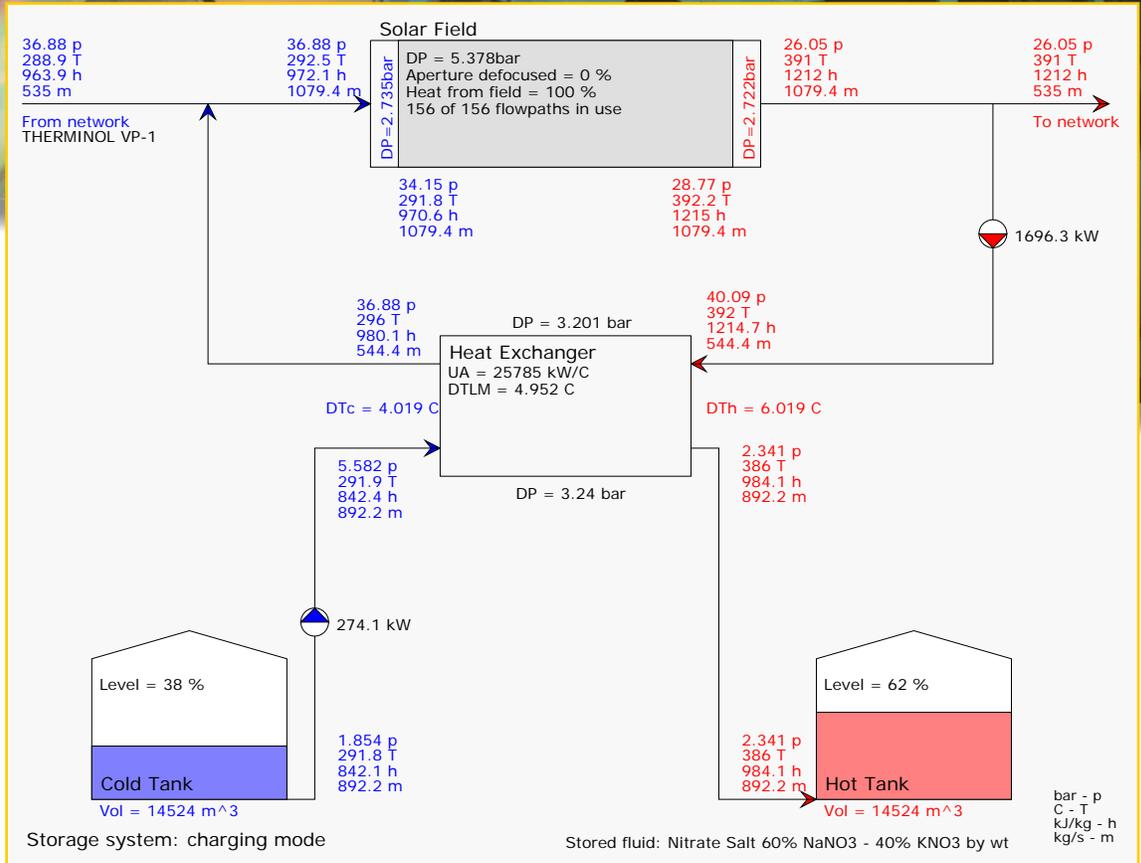
Molten salt is pumped from tank to tank through the salt-to-oil storage HX as the storage system charges and discharges. When the solar field captures more heat than is needed by the power plant, some thermal oil flows through the storage HX to heat the salt flowing from the cold tank to the hot tank. This charges the storage system with the excess field heat. In contrast, when the solar field absorbs less heat than is needed to run the power plant, cool thermal oil flows in the other direction through the heat exchanger where it is heated by salt flowing from the hot tank to the cold tank. Thermal oil heated by the storage system is combined with any oil

heated by the field and used to make steam for the power plant. Discharging the storage allows the power plant to make power when needed or desired, as opposed to being held entirely captive by the sun's availability.

Solar fields with two tank storage systems have been designed to provide between six and twelve hours of full load power without sunshine.

Andasol 1 Plant Model

THERMOFLEX was used to create the model shown to the left. It is a 50 MW reheat Rankine cycle similar to the Andasol 1 solar thermal power plant located in Granada, Spain. It has five feedwater heaters and steam is condensed in a water cooled condenser serviced by a wet cooling tower. A solar boiler with parallel



Daily Plant Operation

reheater produces and reheats steam in shell-tube heat exchangers. The heaters use hot thermal oil (Therminol VP-1) provided by the solar field. A two-tank molten salt storage system is used to store excess heat generated by the oversized solar field, when possible.

Steam conditions are lower than with fossil fired plants because they are limited by thermal oil operating temperatures. Nominal steam turbine conditions are 100 bar, 381 C at HP admission, and 18 bar, 381 C at reheat admission. At nominal conditions, approximately 535 kg/s of hot thermal oil is required to run the power plant.

The solar field consists of a large number of parabolic trough collectors that focus solar energy on a receiver tube carrying the thermal oil. The oil is heated as it passes through the field.

The solar field is sized at noon on the Vernal equinox with a solar multiple of 1.5. The storage system capacity is 1045 MWhr, and the storage heat exchanger is rated at just under 140 MW. Operating on storage alone, this plant can operate for about 7.5 hours at rated discharge capacity. The model was developed using ambient conditions typical of the Andasol 1 location in southern Spain (37.1 north latitude, 1100 masl).

The solar field is oversized for summer operation and can heat almost twice as much fluid at noon than is

needed to run the power plant at its rated load. The solar field and storage system are modeled together in a single icon (#16) which has built-in logic to charge and discharge the storage system as the field heating ability changes throughout the day.

This system is 100% solar; there is no backup thermal oil heater to provide heat when the solar field is out of service, or unavailable due to a lack of sunshine.

Simulation of Daily Plant Operation

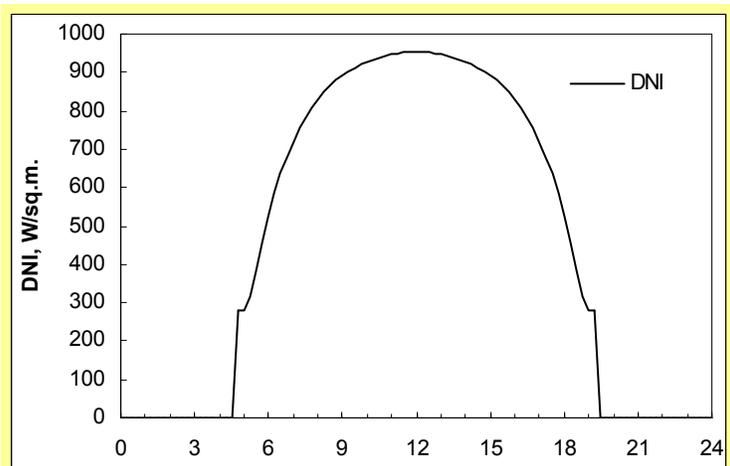
Storage system operation is naturally a time-dependent process. THERMOFLEX calculates steady-state models, so modeling plant operation with storage is done with a quasi-steady approach using a series of runs, each representing a single slice of time where the plant is assumed to operate in steady-state. E-LINK is the tool used to carry out these runs where the inputs are entered in Excel, and the outputs are presented in Excel.

In Excel, the storage system's state at the end of the current time step is fed forward as the initial condition for the next time step. Quasi-steady modeling is a useful tool for approximating plant operation over long

time periods where the transients encountered are fast relative to the time step.

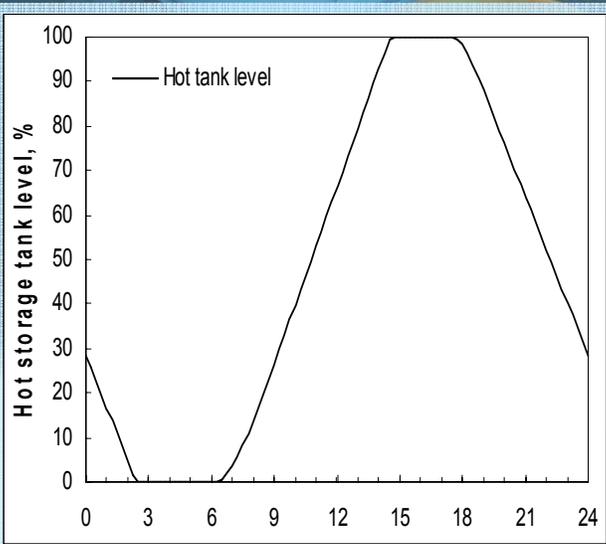
The model shown in preceding page was run from midnight to midnight on day 173, the summer solstice. The initial condition for hot tank storage level is the value computed by the previous day's simulation. THERMOFLEX's built-in solar irradiance model was used to estimate DNI and solar angles throughout the day. The latitude is 37.1 degrees north, the location of Andasol 1 in Granada, Spain.

The following series of charts show variation in selected parameters throughout the day. In each case, the x-axis is solar hour of day.



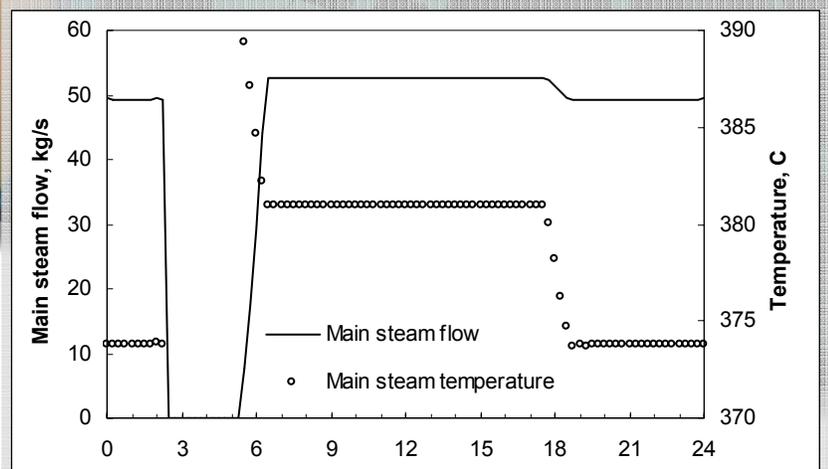
These calculations use irradiance from the built-in sun model. This plot shows computed variation in Direct Normal Irradiance for Day 173 at elevation of 1100m at 37.1° North. This is the key driver governing heat input to the plant.

“ Thermal Storage



Hot and cold tank levels change throughout the day. In this model, the hot tank is about 30% full at midnight, the starting time for this quasi-steady analysis. The hot level drops steadily as the demand for hot oil remains constant. Once the hot tank is empty, the storage system shuts down, and no oil is delivered to the network, so the power plant shuts down.

At about 6:30AM, the field is capable of heating more oil than required by the network. At this time, the storage system goes into charging mode and the hot tank level begins to rise. The rate of rise increases initially as the DNI level rises. Just before 9AM the storage system charge rate hits its limit, and the hot tank level begins to rise at a constant rate. At about 2:45PM the hot tank is full and the storage system cannot absorb anymore heat. At about 5:30PM the storage system begins to discharge because the solar field cannot produce enough hot oil to satisfy demand by itself.



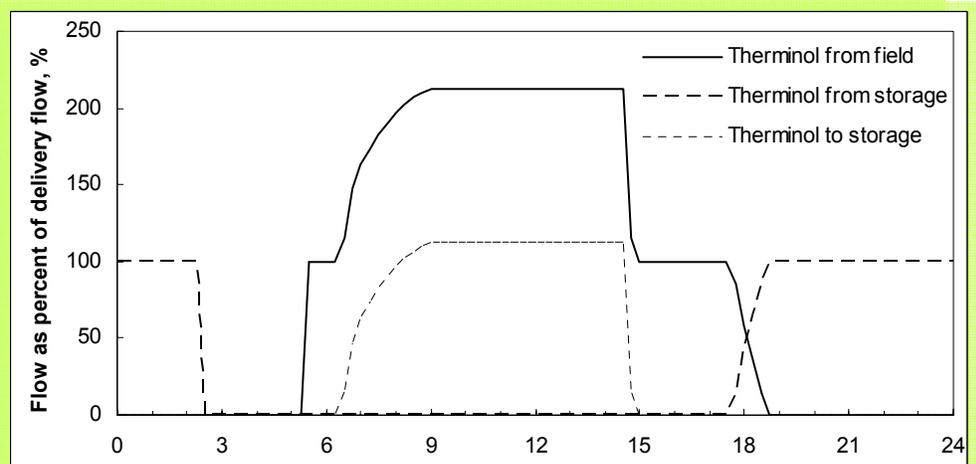
Plant loading in this model is established by setting a desired hot oil flow on the solar field with storage icon, #16 in diagram on previous page. The delivered oil temperature depends on the heating source. When the field heats all the oil, it is available at its design temperature. The oil temperature drops whenever some of the heat comes from storage.

The result is variable steam flow to steam turbine, and variable HP and RHT steam temperatures. This plot shows main steam flow of just below 50 kg/s at 373 C when the storage system is the only heat source. During the day, the steam flow rises by about 4% and is available at 382 C due to higher oil temperature from the field.

This plot shows Therminol flows from the solar field, from the storage system, and to the storage system as a percent of flow delivered to the solar boiler. The solid line shows field flow. The long dashed line shows storage discharge used to makeup field shortfall. The short dashes represent flow used to charge the storage system.

The early summer sunrise allows the field to begin to produce hot oil just after 5AM. Field oil heating continues until almost 7PM. The flowrate increases until just before 9AM when the storage system charge rate hits its maximum due to maximum salt flowrate. This capacity limit is in place until just before 3PM when the storage tank becomes filled to capacity. At this time, the storage system shuts down and mirrors are defocused to restrict field heating to that needed to just meet demand flow. Starting around 5:30PM, the field flow begins to drop because of waning sunlight.

The discharge flow mixes with any field-heated fluid and is delivered at the mixture temperature. During the evening and overnight period the storage system provides all Therminol. During the day-time, the field alone is capable of satisfying flow demand and the storage system is operated in charge mode or is shutdown if it's full.



The field flowrate is large enough to begin to charge the storage system at about 6AM. The charging period that lasts until just before 3PM. The cap in charging flowrate occurs when the storage system charge rate hits its maximum, as implied by maximum salt flowrate from tank to tank. The charging flow quickly drops to zero at about 2:45PM when the hot tank is full.

Hybrid Solar-Fossil Power Plant

Model Overview

The overall heat balance result from a THERMOFLEX model of a proposed hybrid solar-fossil power plant is shown below.

It is a condensing steam turbine power plant with an air-cooled condenser (ACC), a low pressure feed-water heater, and a deaerator. Steam is directly generated in a Linear Fresnel Collector (LFC) solar field and/or by a gas-fired package boiler installed in parallel. The solar field consists of three sections, one to preheat water, one to evaporate water, and the final section to superheat steam. The evaporator is designed to produce 30% quality steam. A steam drum separates the phases; liquid recirculates to evaporator inlet, and dry steam flows to the superheater field. Nominal turbine inlet conditions are 65 bar, 450 C, 13.6 kg/s. Nominal ACC pressure is 125 mbar in a 32 C ambient. This plant design minimizes plant makeup water requirements, consis-

tent with desert-like site conditions present at many solar sites.

This design includes a natural-gas fired backup boiler, in parallel with the solar field, to generate steam when the field is unavailable due to maintenance, weather, or time-of-day. The backup boiler facilitates firm electric dispatch, without storage.

The steam cycle is small, does not include reheat and has few heaters. Therefore the base cycle efficiency is relatively low. However, this plant is also relatively simple, inexpensive, and easily capable of operation in full solar mode, full gas-fired mode, or in hybrid mode when some steam is generated in the field and the balance is provided by the fired boiler. So, it is flexible.

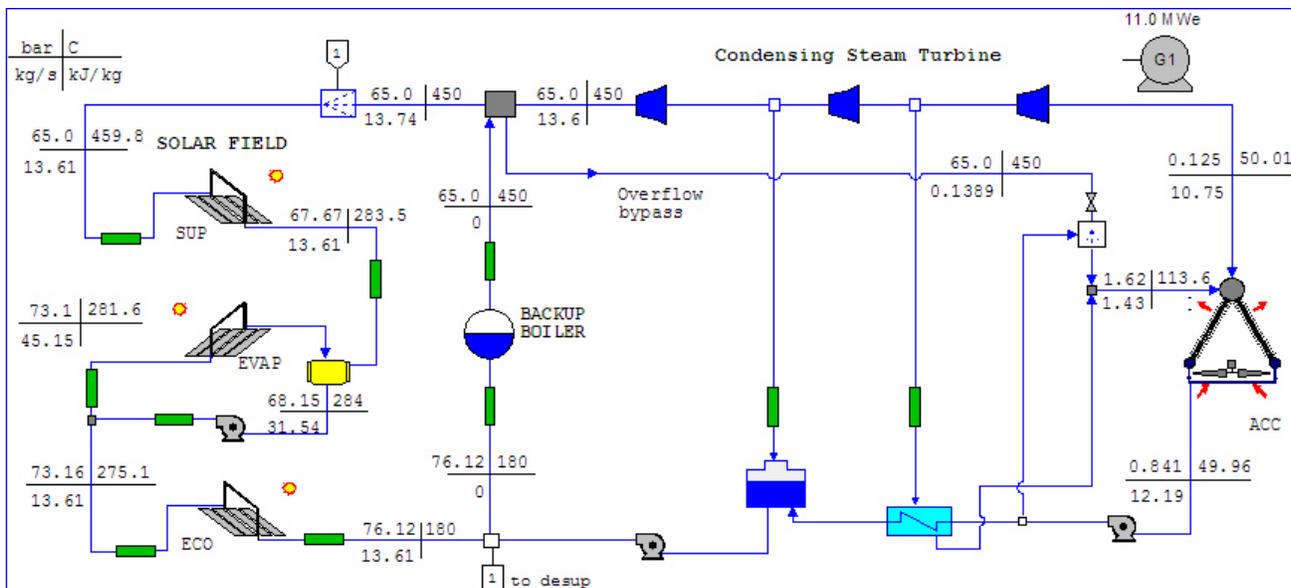
This model was used to simulate operation over a year using ambient and irradiance conditions typical of Daggett California, USA. The plant was run on a 24 hour schedule for

8000 hours per year. The annual average net LHV (lower heating value) efficiency was computed from the sums of net power produced and net fuel consumed; (GWhr electric export / GWhr LHV fuel consumption). Results of the yearly simulation show this relatively low efficiency steam cycle operates at 41% effective net LHV electric efficiency, a high value by Rankine cycle standards. This efficiency would be far higher if the plant were shut down overnight, and would be lower in locations with poorer solar characteristics.

Direct Steam Generation

THERMOFLEX can compute pressure drop and heat transfer for receiver tubes carrying single phase thermal oils, single phase water, two-phase water, and superheated steam. It includes a detailed physical model of thermal-hydraulic behavior of solar fields using Direct Steam Generation (DSG).

Estimates of pressure gradient and



Direct Steam Generation (DSG)

heat transfer coefficient in two-phase flow situations is more complicated than for single-phase situations. THERMOFLEX uses a one dimensional model where the flow path is discretized into a number of steps. The model estimates step-wise local values for internal heat transfer coefficient and pressure gradient based on prevailing flow conditions and physical characteristics of the flow-path including length, roughness and fittings.

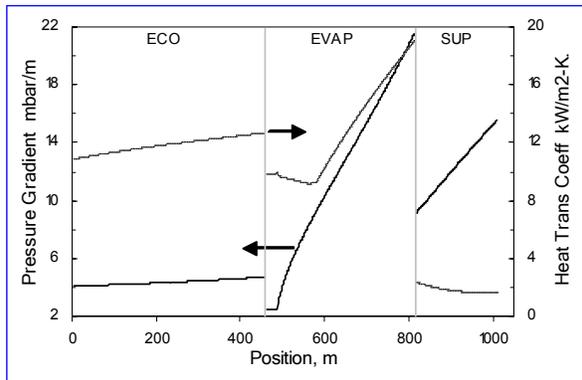
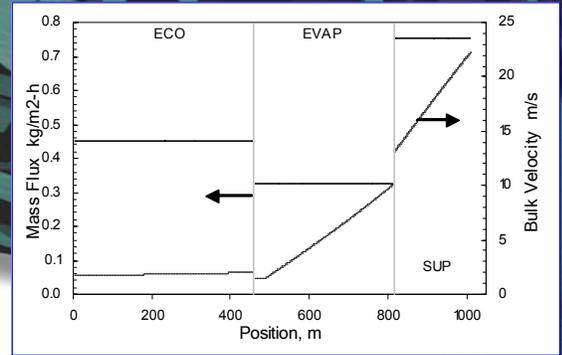
This series of three graphs show distributions of computed pressure, temperature, pressure gradient, heat transfer coefficient, mass flux, and bulk velocity from economizer inlet to superheater exit for this plant model operating at design heat balance conditions. Three distinct regions correspond to the separate fields for heating water, making steam, and superheating steam.

Pressure distribution (below) is discontinuous because of pressure

losses in piping systems between fields. The temperature plot is discontinuous between economizer and evaporator because subcooled

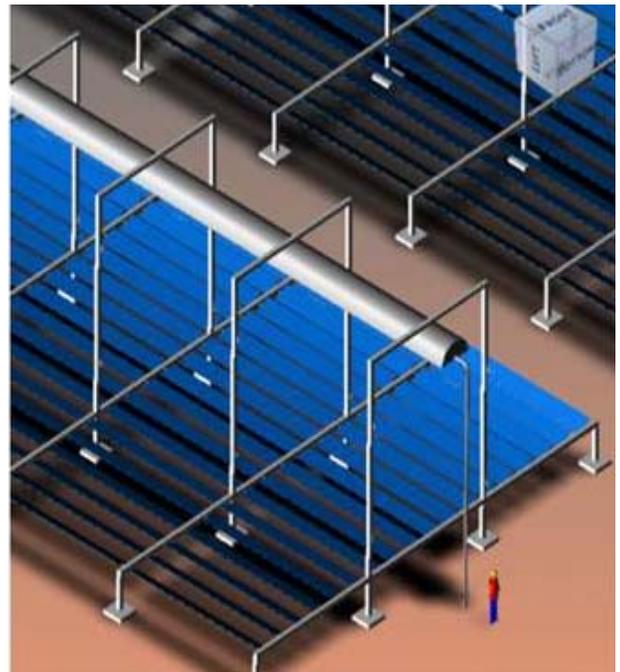
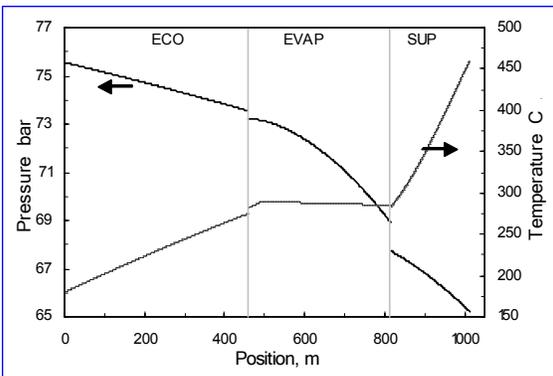
economizer exit water mixes with saturated liquid recirculated back from the steam drum. The final steam temperature exceeds the turbine inlet by 10 C, requiring use of a de-superheater between the solar field and turbine.

The pressure gradient and heat transfer coefficient distributions (above) are discontinuous in value because the mass flux in each field is different, to ensure reasonable velocities in each section. The slope of pressure gradient in evaporator is discontinuous because inlet water is slightly subcooled. The sharp discontinuity in value of heat transfer coefficient between evaporator exit where steam



quality is 30%, and superheater inlet illustrates how dramatically this differs between wet low quality steam and dry vapor.

The number of paths in each field section is different, although the receiver tube diameters are the same throughout (70 mm OD). Therefore, the mass flux in each section is different, and the velocities are discontinuous at field boundaries. Velocity varies inversely with density along the flow path.



THERMOFLEX outputs include a bird's-eye view and a cross-section of the collector. Starting with Version 20, THERMOFLEX provides a 3D view of the solar field as shown here. This helps the user visualize effects of changing collector design, spacing, field ar-

Daily Plant Operation & Annual Yield

Off-design Modeling

Once a plant design is established, off-design simulations are used to compute expected plant performance at site and operating conditions expected during the year. Typically simulations are done at different ambients, solar conditions, load levels, etc. Results are used to map expected plant performance throughout the operating envelope, and to compute yearly totals for power production, fuel consumption, water consumption, etc. Sometimes off-design simulations identify ways to fine-tune the original design so it more effectively satisfies expected duty cycle.

THERMOFLEX models can run in design mode, in off-design mode, or in mixed mode where some components are in design and some in off-design.

With ThermoFlow software, "design"

mode means the user specifies (or THERMOFLEX automatically determines) equipment physical characteristics, general configuration data, and desired thermodynamic constraints. THERMOFLEX computes the heat and mass balance and also determines the equipment size needed to realize the heat balance result. In contrast, "off-design" mode means the equipment size is already established by a design calculation (subject to user edits), and the model computes how equipment of that size operates at user-specified loading, ambient, and solar conditions.

In both modes the computed heat and mass balance parameters are the same, but the method of computing them is different.

E-LINK—Running THERMOFLEX from Excel

E-LINK allows ThermoFlow models

used in formulae, as source data for charts and tables, or linked to other Excel-aware applications. With E-LINK, any number of model runs can be made in a workbook. So, E-LINK is the tool to use for making annual yield calculations where some users make 8760 simulations to map out the year.

Daily Operation

This example uses the hybrid solar-fossil plant with DSG described on the previous page. During the day the solar and ambient conditions change. Prevailing values for these key model inputs are used to predict hourly plant operation. In this model, automated plant loading is accomplished using a steam flow controller icon. This logical component is connected upstream of the steam turbine and regulates steam flow to the turbine so it stays in a specified range. When the solar field makes less than the minimum steam turbine admission flow, the controller automatically draws steam from the backup boiler to makeup the shortfall. If the solar field makes more than the maximum admission flow, the controller shuts down the auxiliary boiler and dumps excess steam to the condenser through a letdown station. The controller's limits maintain steam turbine power between roughly 8 and 11 MW.

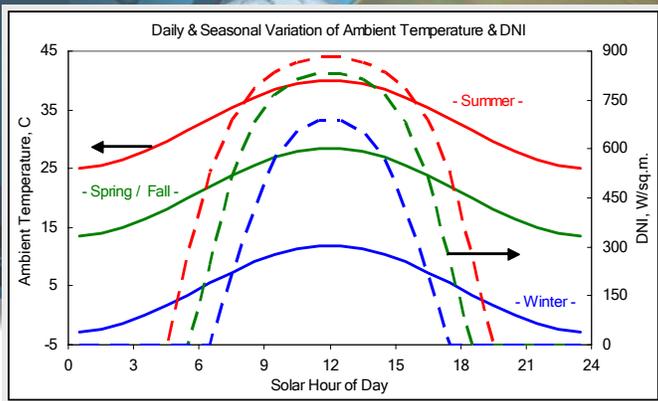
Annual Yield Simulations

Hour-by-hour simulations are used to compute annualized totals and averages. In this example the plant model is the hybrid solar-fossil

| E-LINK 19.0 | | | | | | |
|---|-----------------------------------|------------------|----------------|----------------|----------------|----------------|
| Copyright © 1999-2009, ThermoFlow Inc. | | | | | | |
| Base Case: C:\TFlow\19\MYFILES\S5-10\SolarThermal_Fresnel_DirectSteamGeneration.tfx | | | | | | |
| Loaded: 01-28-2009 16:09:50 | | | | | | |
| Spring / Fall cases | | | | | | |
| INPUT VARIABLE DESCRIPTION | | Units | Messages Input | Messages Input | Messages Input | Messages Input |
| 9 | Ambient temperature | C | 13.6 | 14.1 | 15.0 | 16.4 |
| 10 | Ambient relative humidity | % | 30 | 30 | 30 | 30 |
| 11 | Day of the year | | 264 | 264 | 264 | 264 |
| 14 | Solar hour of the day | | 0.5 | 1.5 | 2.5 | 3.5 |
| 17 | | | | | | |
| OUTPUT VARIABLE DESCRIPTION | | Units | Output | Output | Output | Output |
| 19 | Plant Gross Power | kW | 9014 | 9014 | 9014 | 9014 |
| 20 | Plant Net Power | kW | 8527 | 8526 | 8523 | 8518 |
| 21 | Plant LHV Fuel Heat Input | kW | 31078 | 31078 | 31078 | 31078 |
| 22 | Solar Field Steam Flow | th | 0.00 | 0.00 | 0.00 | 0.00 |
| 23 | Package Boiler Steam Flow | th | 40.4 | 40.4 | 40.4 | 40.4 |
| 24 | Site Direct Normal Irradiance | W/m ² | 0 | 0 | 0 | 0 |
| 25 | Total Steam Flow to Steam Turbine | th | 40.4 | 40.4 | 40.4 | 40.4 |
| 26 | | | | | | |
| 27 | | | | | | |
| 28 | | | | | | |
| 29 | Solar Field Steam Production | % | 0.0 | 0.0 | 0.0 | 0.0 |
| 30 | Fired Boiler Steam Production | % | 100.0 | 100.0 | 100.0 | 100.0 |

E-LINK workbook used to simulate hour-by-hour performance throughout the year. Each column (case) represents one hour. Model inputs are in the yellow region, and computed model results are stored in the blue region. Other cells are normal Excel cells, available for use as needed.

to be run from inside Microsoft Excel. E-LINK is a feature included with any ThermoFlow software license. E-LINK is a great tool for parametric studies, performing batch runs, and making automated calculations. Values for user-selected model inputs are entered in normal Excel cells, and computed results are stored in associated cells. The inputs and outputs are treated like any other Excel cell so they can be



power plant described on the previous page. It is operated on a 24-hour schedule with power levels ranging from just over 8 MW to a maximum of 11 MW. Power limits are established by limiting steam turbine admission flow in a range of 40 to 53.4 t/h.

Here, the hourly inputs and outputs for three particular days are shown to demonstrate how the plant operates under different conditions. Estimated ambient temperature and DNI for particular summer, winter, and shoulder season days are shown in the plot above. The ambient data is from a model of the site in southwestern US, near the Kramer Junction SEGS plants. The DNI is estimated by the program using its theoretical sun model.

Summer conditions are shown in red, winter in blue, and shoulder season in green. The solid lines show ambient temperature which has a strong impact on air cooled condenser performance, and hence steam turbine power production.

DNI (dashed lines) and solar angles vary with solar hour and day of year. These parameters strongly influence steam production in the solar field. The solar angles, not shown, are computed by the program for this location based on the day and the solar hour.

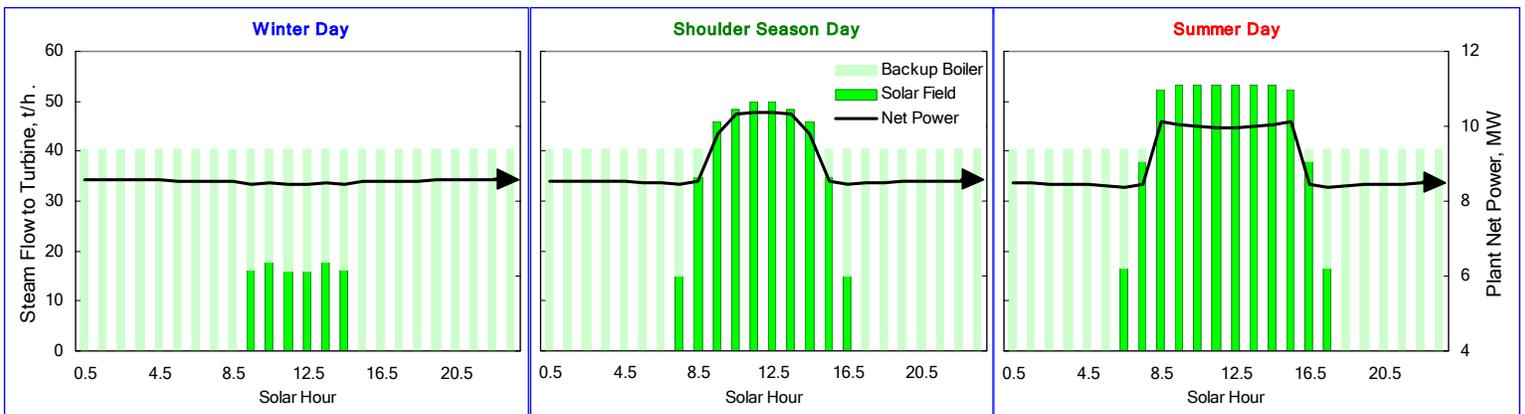
Hour-by-hour simulation results for winter, spring/fall, and summer days are plotted below. Steam turbine flow from the solar field is shown with bright green bars. Flow from the backup fossil-boiler is shown with light green bars. Steam flows are plotted on the left axis in tonne/hour (t/h). Net plant power (MW) is plotted as a solid black line on the right-hand axis.

The solar field cannot make the minimum admission flow at any hour of the winter day. For six hours in the middle of the day the solar field can make about 45% of the steam needed to load the turbine at the minimum power. Throughout the winter day the plant generates a roughly constant power level associ-

ated with minimum steam flow to the turbine.

On the summer day the solar field makes more steam than the turbine can swallow for six hours, and makes all needed steam for eight hours in the middle of the day. During early morning and late afternoon the field can still generate a significant fraction of maximum steam for the turbine.

Plant net power varies throughout the day. The variation is most pronounced in the summer and shoulder season. This variation is the result of two effects. First, the admission steam flow varies throughout the day. Increased steam flow to the turbine raises its output power. Second, the air cooled condenser's capacity varies throughout the day. During the hottest parts of the day the capacity is reduced which in turn reduces steam turbine gross power. The model accounts for these effects automatically, consistent with plant equipment capacity.



Integrated Solar Combined Cycle (ISCC)

Integrated Solar Combined Cycle (ISCC)

Integrated Solar Combined Cycle plants are a gas turbine combined cycle with a solar thermal plant to add heat to the combined cycle. While solar-captured heat may be incorporated in many ways; it is typically introduced as high pressure saturated steam, mixed with HRSG HP steam, and superheated for admission to the steam turbine. THERMOFLEX can readily model this, or any other arrangement under consideration.

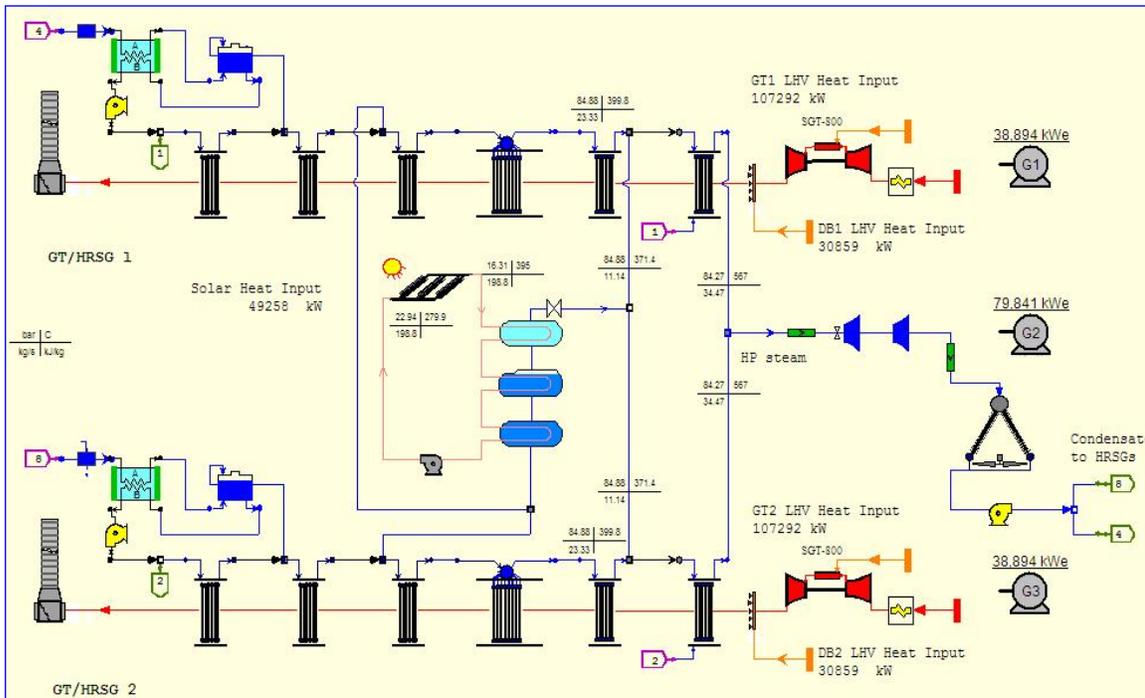
Medium to large scale (100 to 500 MW) ISCC plant designs have been proposed where the solar contribu-

tion is used to augment plant capacity, or to replace gas-fired duct burners to generate extra steam during peak power demand periods. In many warm locations, power demand peaks in the mid-day hours of the summer when significant air conditioning loads occur. This demand profile is well-matched to a solar field's capacity profile.

THERMOFLEX together with GT PRO deliver rapid plant scoping capability together with flexible plant modeling features. Here, GT PRO was used to create the initial plant model, where solar heat input was modeled as an "external heat addition". Afterwards, the GT PRO de-

sign was imported to THERMOFLEX and the solar field and solar boiler were added to generate steam in the model shown below.

The plant design is derived from a heat balance provided courtesy of Siemens Industrial Turbomachinery. It is a 2x1 ISCC with two Siemens SGT-800 gas turbines exhausting into fired single pressure HRSGs making steam for admission to a condensing steam turbine. Steam is condensed in a dry air-cooled condenser. The parabolic trough solar field nominally adds 50 MWth to augment HP steam generated in the HRSG.



Under desert-like ambient conditions, 35 C, 35% RH, 928 mbar, and with 49.3 MWth heat input from the solar field, the plant generates 157.6 MW gross electric output using 276.3 MWth LHV fuel input. Considering the fuel-free solar contribution, the plant operates with a 57.1% gross LHV electric efficiency, considerably higher than typically achieved with one pressure non-reheat GTCC plants.

THERMOFLEX model of a heat balance provided courtesy of Siemens Industrial Turbomachinery. It is a 2x1 ISCC with two Siemens SGT-800 gas turbines exhausting into fired single pressure HRSGs making steam for admission to a condensing non-reheat steam turbine. Model includes a parabolic trough solar field that adds just over 49 MWth to the plant as saturated HP steam. The solar-generated steam is about 80% of duct burner heat input at this condition, and represents about 32% of the steam flow to the steam turbine.

Solar Thermal Desalination

Solar Thermal Desalination

Desalination of sea and brackish water to produce fresh water for domestic and industrial uses is becoming increasingly important in many places around the world. Presently, the major desalination processes in use are Reverse Osmosis (RO), Multi-Effect Distillation (MED), and Multi-Stage Flash (MSF).

Electrically-driven RO is typically used in small to medium-scale water production facilities. Thermally-driven MED and MSF use low to moderate grade heat, and are used in most of the medium to large-scale systems installed today.

THERMOFLEX together with PEACE can model these desalination processes at the design-point and at off-design conditions. Model results include detailed thermodynamic states, performance metrics, and installed system cost estimate.

The THERMOFLEX model below was supplied courtesy of Solar Power Group, GmbH. It models water & power producing plant in the coastal Surt region of Libya, owned by the Libyan Ministry of Energy. Nominally, this plant produces 15,000 m³ per day (3 MIGD) of potable water and has 15 MWnet electric capacity.

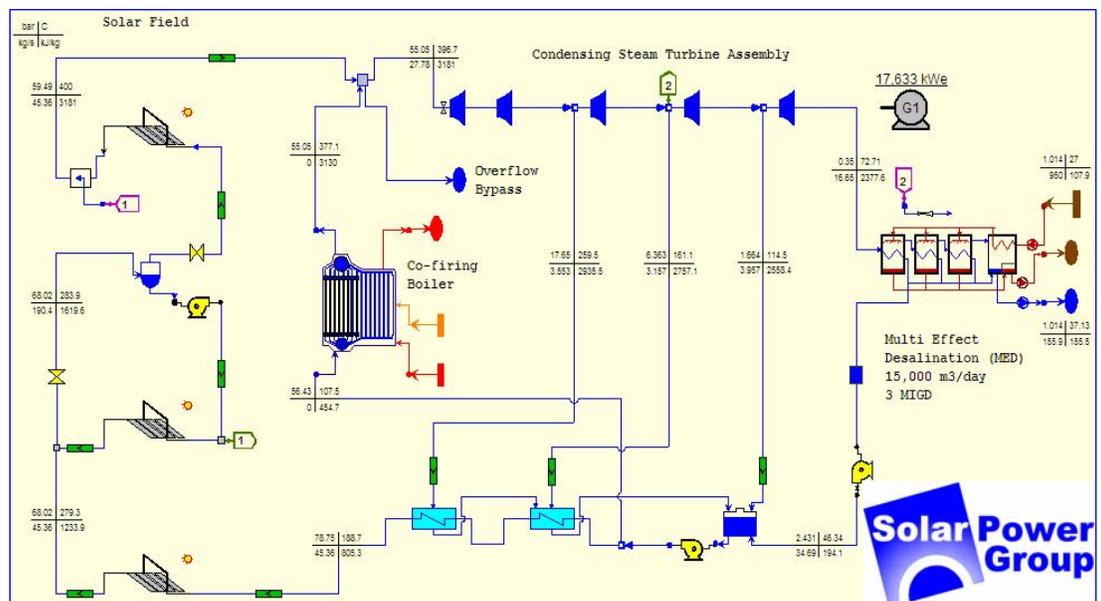
Heat input is provided by the combination of a solar field and natural gas-fired boiler, installed in parallel. This solar-fossil hybrid design leverages the site's sunny climate and its proximity to natural gas fields. The hybrid design can produce power and water 24 hours per day without a solar storage system. The desalination system condenses steam turbine exhaust and produces potable water from seawater. It takes the place of what would be a steam condenser in a pure power plant.

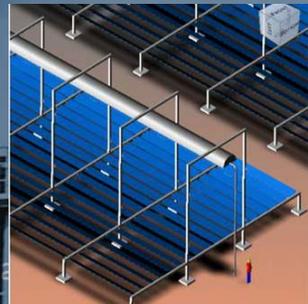
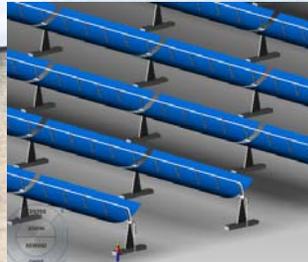
The solar field uses Linear Fresnel Collectors (LFC) with direct steam generation (DSG). It consists of three sections; one to preheat water, one to evaporate water, and the final section to superheat steam. The evaporator is designed to produce 30% quality steam. A steam drum separates the phases; liquid recirculates to evaporator inlet, and dry

steam flows to the superheater field.

A single-casing steam turbine operates at high speed with a reduction gear coupled to a synchronous generator. Nominal turbine inlet steam conditions are 55 bar, 400 C. Three steam extractions provide steam to a deaerator and two higher-pressure feedwater heaters. Water is preheated to about 190 C before the economizer section of the solar field. Feedwater to the gas-fired boiler comes directly from the feedpump.

The desalination system is comprised of two parallel units, each having a nominal capacity of 7,500 m³ per day (1.5 MIGD). The MED design has a nominal performance ratio of 10.4 (gain output ratio of 9.4). This high level of efficiency is achieved by using twelve effects over a temperature range of 30 C.





Starting in 1987 with its flagship program GT PRO™, Thermoflow's software suite has grown to include seven powerful, yet easy-to-use tools to analyze the spectrum of power generating technologies in use today, and under consideration to meet tomorrow's demanding challenges.

As of 2010, Thermoflow has sold over 7200 program licenses to companies in 75 countries. This proven track record makes Thermoflow's software suite the most widely-used, and well-respected in the power generation industry.

A complete list of Thermoflow customers is available at www.thermoflow.com. A small sampling is listed below.

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- ☼ Lahmeyer International ☼ Electricite de France ☼ SUEZ Tractebel ☼ Fraunhofer ISE ☼
- ☼ Siemens CSP (Solel) ☼ Office National de l'Electricite (ONE) ☼ Renewable Energy Systems (RES) ☼
- ☼ BTU Industries ☼ Lockheed Martin ☼ Ecolaire Espana ☼ Bechtel Power ☼ Black & Veatch ☼
- ☼ Chiyoda ☼ Duke ☼ Fluor ☼ Hyundai ☼ PB Power ☼ Stone & Webster ☼ Toyo ☼ TransCanada Power
- ALSTOM ☼ CMI Boilers ☼ Hangzhou Boiler ☼ Foster Wheeler ☼ General Electric ☼ Kawasaki ☼ Harbin
- Turbine ☼ Mitsubishi ☼ Rolls-Royce ☼ Solar Turbines ☼ Dong Fang Turbines ☼ Akzo ☼ BP ☼ British
- Energy ☼ Chevron ☼ ConocoPhillips ☼ ExxonMobil ☼ Tokyo Gas ☼ Total S.A. ☼ TransAlta Energy ☼ MIT
- ☼ China TPRI ☼ Korea EPRI ☼ Taiwan Power ☼ Univ. di Bologna ☼ Univ. of Calgary ☼ Univ. di Florence
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