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A Simple Energy Calculation Method for Solar Industrial Process Heat Steam Systems

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A SIMPLE ENERGY CALCULATION METHOD FOR SOLAR INDUSTRIAL PROCESS HEAT STEAM SYSTEMS

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ABSTRACT

Designing a solar industrial process heat (IPH) system, sizing its components and predicting its annual energy delivery requires a method for calculating solar system performance. A calculation method that is accurate, easy to use, accounts for the impact of all important system parameters, and does not require use of a computer is described in this paper. Only simple graphs and a hand calculator are required to predict annual collector field performance and annual system losses.

The energy calculation method is applicable to a variety of solar system configurations. However, this paper describes the calculation method applied only to parabolic trough steam generation systems that do not employ thermal storage. Both flash tank and unfired-boiler steam systems are covered. Readers interested in application of this calculation method to other collector types and/or system configurations are referred to Design Approaches for Solar Industrial Process Heat Systems (Kutscher et al. 1982).

NOMENCLATURE

A_c	collector area (m^2)
$A_{c,max}$	maximum collector area for no-storage system (m^2)
A_g	ground area covered by collector array (m^2)
c_p	constant-pressure specific heat (J kg^{-1} $^oC^{-1}$)
f	concentrator focal length (m)
F'	collector efficiency factor
F_B	unfired boiler factor
F_F	flash steam system factor
F_R	collector heat removal factor
F_S	system dependent heat exchange factor
F_{shade}	annual shading loss factor for midfield collectors
$F_{shade,field}$	annual shading loss factor for collector field
F_{use}	solar system use factor
GCR	ground cover ratio of solar collector array
h_{fg}	water latent heat of vaporization (J kg^{-1})
$HR_{solar\ downtime}$	total expected daytime hours of solar system downtime on an annual basis (hr yr^{-1})
$HR_{process\ downtime}$	total expected daytime hours of industrial process downtime on annual basis (hr yr^{-1})
I	beam irradiation incident in collector plane (W m^{-2})
$\overline{I}_b$	long-term average direct normal irradiance (W m^{-2})
I_{max}	peak irradiance available to collectors (W m^{-2})
$\overline{K}_{\tau\alpha}$	incident-angle modifier annual correction
K_x	collector incident-angle modifier at x degrees
L	latitude (degrees)
L_c	collector length (m)
L_{end}	spillage end loss factor
$\dot{M}_c$	collector field fluid mass flow rate (kg s^{-1})
$\dot{M}_s$	steam mass flow rate (kg s^{-1})
$(Mc_p)_{coll}$	total collector field thermal capacitance (J $^oC^{-1}$)
$(Mc_p)_{sys}$	total thermal capacitance of solar system excluding collector thermal capacitance (J $^oC^{-1}$)
$N_{d,c}$	average number of collection days (cooldown days) per year (days yr^{-1})
$\underline{N}_R$	number of parallel collector rows
$\dot{q}_c$	long-term average energy collection rate of collectors, per unit collector area, during daylight hours (W m^{-2})
Q_c	long-term average annual energy collection of solar system (J yr^{-1})
$\overline{\dot{Q}}_c$	long-term average energy collection rate of collectors during daylight hours (W)
$\overline{Q}_{cool}$	annual solar system cooldown losses (J yr^{-1})
Q_d	long-term average annual energy delivery (J yr^{-1})
$\dot{Q}_{load}$	industrial process energy use rate (W)
Q_{load}	industrial process annual load (J yr^{-1})
$Q_{o,sys}$	average overnight energy loss from piping system components (J day^{-1})
$Q_{o,coll}$	average overnight energy loss from collectors (J day^{-1})

T_a	ambient temperature (^oC)
$\bar{T}_a$	average yearly daytime temperature (^oC)
$T_{a,max}$	highest expected annual ambient temperature (^oC)
$\bar{T}_{a,n}$	average yearly nighttime ambient temperature (^oC)
T_f	collector fluid temperature (^oC)
T_{feed}	boiler feedwater temperature (^oC)
T_s	steam temperature (^oC)
U_L	collector heat loss coefficient ($W\ m^{-2}\ {}^oC^{-1}$)
U_L'	modified collector heat loss coefficient (modified for pipe system losses) ($W\ m^{-2}\ {}^oC^{-1}$)
U_bA_b	unfired boiler heat transfer coefficient, boiler surface area product ($W\ {}^oC^{-1}$)
U_iA_i	overall heat loss coefficient of piping system components on outlet (hot) side of field ($W\ {}^oC^{-1}$)
U_oA_o	overall heat loss coefficient of piping system components on inlet (cold) side of field ($W\ {}^oC^{-1}$)
$(UA)_{sys}$	heat loss coefficient of entire piping system ($W\ {}^oC^{-1}$)
$(UA)_{tot}$	total solar system thermal loss coefficient ($W\ {}^oC^{-1}$)
W_x	incident angle modifier weighting factor for x degrees

INTRODUCTION

During the planning and design stages of an IPH solar system, an annual energy calculation method is needed for two principal reasons. First, a calculation method is needed to aid in the design of the solar system. Various solar system configurations must be analyzed, alternate solar collectors must be compared, and the collector field and other system components must be sized. Second, an evaluation of the cost effectiveness of the solar system (i.e., payback period or internal rate of return) requires an estimate of annual solar system energy delivery.

A number of items impact the energy delivery of a solar system, including collector field size and orientation, collector characteristics, site characteristics, collector fluid properties and process load characteristics. Because there are so many variables, detailed computer models are often employed to make IPH system tradeoffs and to provide the necessary performance information. However, this approach requires computer facilities, is time-consuming, and can be expensive. The design engineer prefers design tools that are easy to use and provide for a quick assessment of various design options. Fortunately, design tools can be greatly simplified with the use of simple modifiers that have been analytically calculated. A familiar example is the heat removal factor F_R (Duffie and Beckman, 1974), which accounts for the performance impact of the temperature rise across the collector field. However, not all solar system component variables can be characterized in this manner because of their time-varying behavior. Instead, by appropriately grouping time-varying variables into meaningful groups and using regression analysis techniques, their performance impact can be correlated empirically.

Ideally, empirical correlations should be based on measured data from operating solar systems, but suitable data for solar IPH systems is not yet available. Instead, the empirical correlations that have been developed are based on the results of a detailed, hour-by-hour IPH system computer model called SOLIPH. Another paper in these proceedings describes the computer model (Kutscher, 1983). Typical meteorological year (TMY) tapes provided the hourly weather and solar irradiation data base for the computer model. The TMY data set is a composite of months selected from the SOLMET historical data base for each of the 26 stations with long-term records. For these SOLMET stations, thousands of SOLIPH runs were made to provide a large data base for developing empirical correlations. With this large data base, a multivariable regression analysis was used to generate empirical correlations that closely matched the SOLIPH runs. Agreement between the empirical correlations and the SOLIPH runs is better than 4% (rms error). Additionally, these empirical correlations were checked for accuracy against a larger weather and solar irradiation data base. SOLIPH runs for the 208 ERSATZ sites (using ERSATZ TMY tapes) were made and compared with the empirical correlations. Again, empirical correlation accuracy (rms error) was found to be better than 4%.

SOLAR IPH STEAM SYSTEMS

A large amount of industrial process heat is utilized in the form of low-pressure saturated steam. A large fraction of this energy is utilized by industrial plants that have daytime, 7 day/week loads. For these industrial plants, a no-storage, solar-steam system can provide an attractive source of thermal energy.

There are currently two principal configurations for solar system steam production *. The first and most widely used system configuration is the unfired-boiler system (see Fig. 1). This is the configuration used by all five MISR program participants. In an unfired-boiler steam system, heat transfer fluid is pumped through the collector field and then to an unfired boiler. The hot fluid within the tubes of the boiler vaporizes water in the shell and saturated steam is fed to the existing steam header that delivers energy to the industrial process. As the steam is generated, make-up condensate is supplied to the boiler. To account for the temperature elevation of the collector loop inlet above the steam temperature a simple modifier is introduced--the unfired boiler factor, F_B. Derivation of the unfired boiler factor is provided in Ref. 5.

In a flash-steam solar system (see Fig. 2), pressurized water is circulated through the collector field and flashed to low-quality steam across a throttling valve into a separator tank. Flashing is a constant enthalpy process that converts the sensible heat of the water into a two-phase mixture of water and steam at conditions prevailing in the flash tank. The steam quality (fraction of total mass flow that is flashed to vapor) usually is less than 10%. Steam separated in the flash tank is fed into the plant steam distribution system to be used by the industrial process. The saturated liquid is recirculated through the collector field. To maintain the necessary liquid level in the flash tank, boiler feedwater is injected into the pump suction.

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*A third configuration for steam generation is described elsewhere in these proceedings (May and Murphy, 1983).

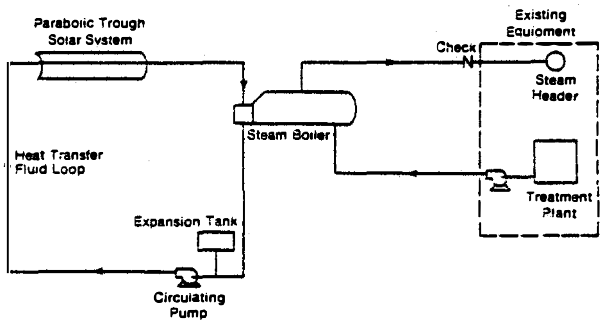

Fig. 1 - Unfired Boiler Steam System

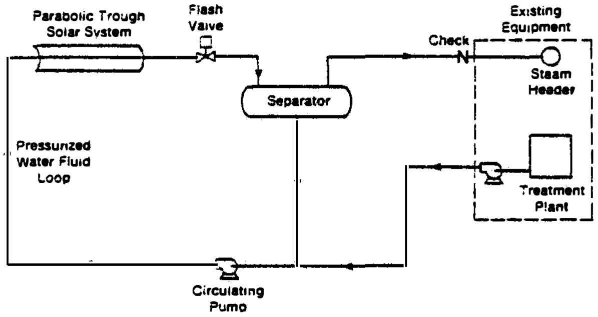

Fig. 2 - Steam Flash System

To prevent boiling within the collector, the water is pressurized by the recirculation pump. The pump is specified so that water exiting the collector field is under sufficient pressure to prevent boiling. The collector field outlet temperature must be considerably above the steam delivery temperature to obtain reasonable steam qualities downstream of the throttling valve and reduce the water recirculation rate. Another simple performance modified accounts for this temperature elevation—the flash system factor F_F. The flash system factor derivation is given in Ref. 5.

STEP-BY-STEP PROCEDURE

A step-by-step calculation procedure for the annual energy collection of a no-storage IPH solar steam system is provided below. The inputs required of the industrial owner or system designer are all readily available items of information.

Step 1 - Obtain necessary information.

- Define process steam temperature T_s and boiler feedwater temperature T_{feed}. Check that a steam requirement exists during daylight hours, 7 days/ week.
- Define latitude L, yearly average daytime temperature $\overline{T}_a$ and yearly average nighttime temperature $\overline{T}_{a,n}$ of proposed site. Average temperatures can be found in the U.S. Climatic Atlas and other reference books. As a close approximation, the average nighttime temperature can be taken as $\overline{T}_a - 6°C$.
- For the solar collector that is to be used, obtain its $F'U_L$ and $F'\eta_o$ values and its incident-angle modifier curve. This information should be taken from test data measured at an independent testing laboratory.

Often parabolic trough efficiency is reported as:

$$\eta_c = A_1 - B_1 \frac{T_f - T_a}{I} - B_2 \left(\frac{T_f - T_a}{I}\right)^2$$

This efficiency form has no physical basis (Tabor, 1980) and should be modified to the suggested form shown below.

$$\eta_c = A_1 - B_1 \frac{T_f - T_a}{I} - B_2' \frac{(T_f - T_a)^2}{I}$$

$$\text{where } B_2' = B_2/I_{test}$$

I_{test} is the beam irradiance that was present during the collector test. If no I_{test} value is given, take I_{test} as 1000 W/m^2.

Now, the collector $F'\eta_o$ and $F'U_L$ are given as:

$$F'\eta_o = A_1 \text{ and } F'U_L = B_1 + B'_2(\Delta T).$$

Evaluate $F'U_L$ at $\Delta T = T_s - \overline{T}_a$.

- Define land availability at proposed solar site.

Step 2 - Configure collector field and energy transport system. (Collector manufacturer recommendations as well as references (8, 9, 11 and 12) will aid in this step.)

- Calculate the maximum recommended collector area $A_{c,max}$ based on the process load energy use rate Q_{load} and assuming no thermal storage is used and that solar energy is never dumped.

  $$A_{c,max} = \dot{Q}_{load}/[F'\eta_o I_{max} - F'U_L(T_s - T_{a,max})] \quad .$$

  $$\text{where } \dot{Q}_{load} = \dot{M}_s \left[h_{fg} + c_p\,(T_s - T_{feed})\right]$$

  I_{max} can be estimated as 1100 W m^{-2}. A more accurate estimate can be found in ASHRAE Clear Day Solar Intensity Tables (ASHRAE Fundamentals, Chapter 26).

  $T_{a,max}$ may be estimated for the site from ASHRAE for many cities. As a close approximation, a value of 40°C may be used as the maximum temperature for much of the United States.

- Use $A_{c,max}$ as an upper bound in sizing the collector field. Smaller collector fields may be required due to land area limitations, investment considerations, or available sizes of modular collector systems.
- Layout collector field and determine collector field flow rate $\dot{M}_c$.
- Size energy transport piping insulation and expansion tank. Calculate number of pipe supports and valves.

Step 3 - Calculate $F_R\eta_o, F_RU_L$.

- Calculate F_R/F' (F_R accounts for the temperature rise across the collector field).

$$\frac{F_R}{F'} = \frac{\dot{M}_c c_p}{A_c F'U_L} [1 - \exp - (F'U_L A_c/\dot{M}_c c_p)] \quad .$$

$$F_R\eta_o = \frac{F_R}{F'} F'\eta_o$$

$$F_RU_L = \frac{F_R}{F'} F'U_L$$

Step 4 - Calculate system dependent heat exchange factor F_S.

- For steam flash systems, calculate F_F.

$$F_s = F_F = \left[1 - \frac{A_cF_RU_L/\dot{M}_cc_p}{h_{fg} + c_p\,(T_s - T_{feed})}\,(T_s - T_{feed})\right]^{-1}$$

- For unfired-boiler systems, calculate F_B.

$$F_s = F_B = \left[1 + \frac{A_cF_RU_L}{\dot{M}_cc_p(e^{U_bA_b/\dot{M}_cc_p} - 1)}\right]^{-1}$$

Step 5 - Calculate effective optical efficiency.

- Define expected dirt and dust optical loss modifier. Because this loss is site specific it should be based on observed material coupon degradation for the particular site. (See Refs. 4 and 10 for more information.)
- Calculate incident-angle modifier annual correction $\overline{K}_{\tau\alpha}$.

$$\overline{K}_{\tau\alpha} = W_{7.5}K_{7.5} + W_{22.5}K_{22.5} + W_{37.5}K_{37.5} + W_{52.5}K_{52.5} + 67.5K_{67.5}$$

Values of W_x are found in Table 1. Values of K_x are taken from the collectors incident angle modifier curve.

- Multiply the normal incidence optical efficiency ($F_R\eta_o$) by both modifiers to arrive at the effective optical efficiency ($F_R\overline{\eta}_o$).

Step 6 - Modify collector heat loss coefficient and effective optical efficiency to account for thermal transport energy losses.

- Group energy transport components (i.e., piping, valves, fittings, pipe anchors, circulation pump, flex hoses, and unfired boiler or flash tank) into either inlet (cold) components or outlet (hot) components. Calculate U_iA_i and U_oA_o.
- Correct the effective optical efficiency to account for steady-state pipe losses.

$$\frac{F_R\overline{\eta}'_o}{F_R\overline{\eta}_o} = e^{-U_oA_o/\dot{M}_cc_p}$$

- Correct the collector heat loss coefficient to account for steady-state pipe losses.

$$\frac{F_RU_L'}{F_RU_L} = e^{-U_oA_o/\dot{M}_cc_p}\left[e^{-U_iA_i\dot{M}_cc_p} + \frac{\dot{M}_cc_p}{A_cF_RU_L}\,(e^{U_oA_o/\dot{M}_cc_p} - e^{-U_iA_i/\dot{M}_cc_p})\right]$$

Step 7 - Calculate net annual average energy collection rate (taking into account thermal transport losses) for unshaded collectors.

- Determine value of intensity ratio $F_RU_L'(T_s - \overline{T}_a)/(F_R\overline{\eta}'_o\,\overline{I}_b)$ and locate on x-axis of Fig. 3.

  Use Fig. 4 to determine long-term average direct-normal irradiance $\overline{I}_b$.
- Locate value of $\overline{\dot{q}}_c/[F_sF_R\overline{\eta}'_o(\overline{I}_b + 50)]$ on y-axis of Fig. 3 consistent with the intensity ratio, site latitude, and collector orientation.

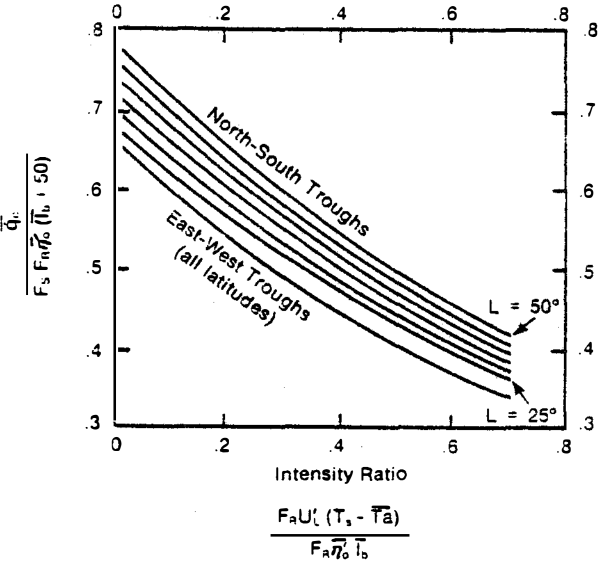

Fig. 3 - Energy Collection Rate Curves vs. Intensity

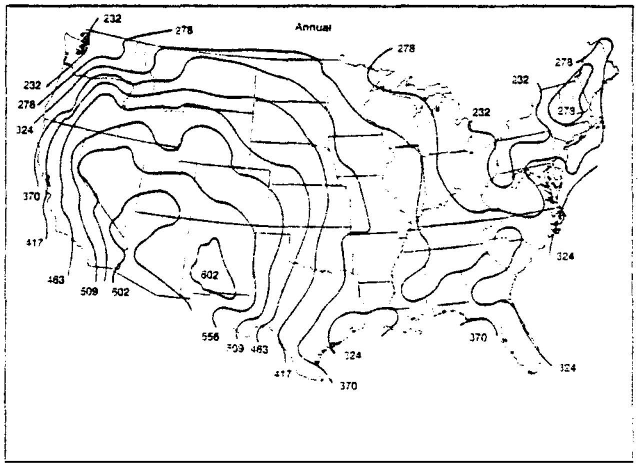

Fig. 4 - Average Direct Normal Irradiance During Daylight Hours (Wm^{-2})

- A hand calculator may be used to evaluate $\dot{q}_c/[F_sF_R\overline{\eta}'_o\,(\overline{I}_b + 50)]$ instead of the graphical determination.

  For east-west parabolic troughs:

$$\overline{\dot{q}}_c/[F_sF_R\overline{\eta}'_o\,(\overline{I}_b + 50)] = 0.6688 - 0.6745 \cdot X - 0.3166 \cdot X^2$$

  For north-south parabolic troughs:

$$\overline{\dot{q}}_c/[F_sF_R\overline{\eta}'_o(\overline{I}_b + 50)] = 0.8810 - 0.8117 \cdot X + 0.3130 \cdot X^2 - 0.003919 \cdot L + 0.003864 \cdot L \cdot X - 0.001484 \cdot L \cdot X^2$$

where L = latitude (degrees)

$X = F_RU_L'(T_s - \overline{T}_a)/(F_R\overline{\eta}'_o\overline{I}_b)$

- Multiply y-axis value by F_s, $F_R\overline{\eta}'_o$, and ($\overline{I}_b + 50$) to determine $\dot{q}_c$.

Step 8 - Calculate annual shading loss factor and annual end loss factor.

- Determine proposed ground cover ratio (GCR = collector aperture width/ row-to-row spacing).
- Calculate required collector field size as $A_g = A_c/GCR$.
- Determine whether enough collector field area is available. If not, increase GCR or reduce A_c.
- Locate annual shading-loss factor (F_{shade}) on Figs. 5 or 6 for specified GCR and latitude of site.
- Calculate field shading loss factor, accounting for one unshaded row.

$$F_{shade,field} = \frac{1 + (N_R - 1)\,F_{shade}}{N_R}$$

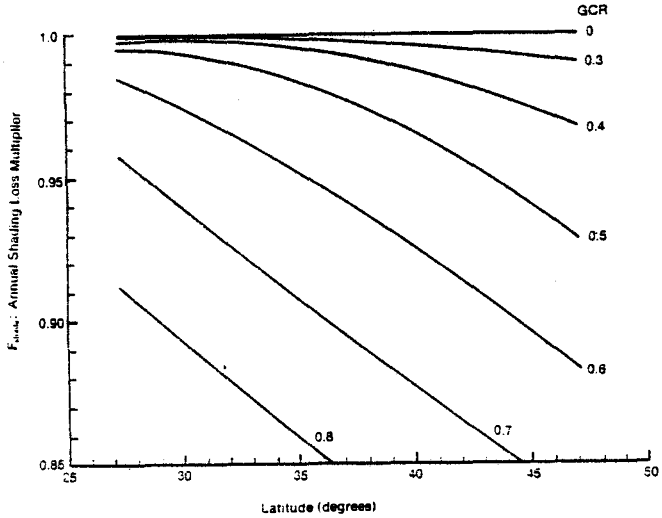

Fig. 5 - Annual Shading Loss Multiplier vs. Latitude for EW Troughs

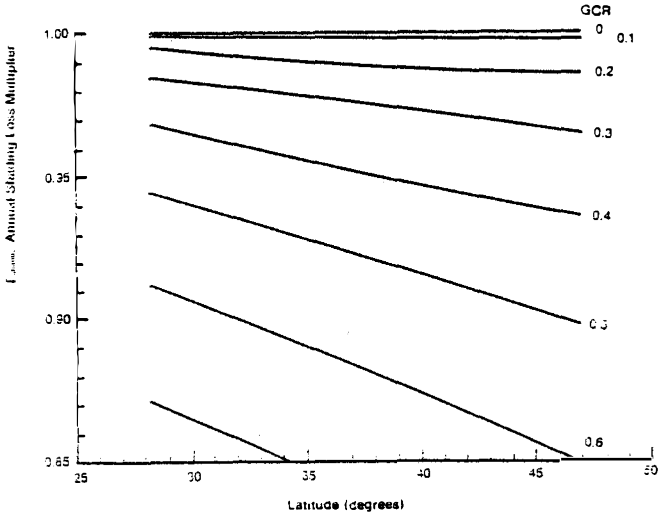

Fig. 6 - Annual Shading Loss Multiplier vs. Latitude for NS Troughs

- Correct $\bar{\dot{q}}_c$ for shading losses by multiplying by $F_{shade,\ field}$.
- Determine end-loss factor for specified row length (see Fig. 7).
- Correct $\dot{q}_c$ for end loses by multiplying by L_{end}.

Step 9 - Calculate net annual energy collection (taking into account thermal transport losses).

Multiply the energy collection rate per unit of collector area $\bar{\dot{q}}_c$ by the collector area A_c to determine $\dot{Q}_c$, the average annual energy collection rate of the collector field.

- Since $\bar{\dot{Q}}_c$ is an average collection rate (in W) based on all daytime hours, multiply $\dot{Q}_c$ by 1.5768×10^7 (the number of daylight seconds in a year) to obtain annual energy collection in Joules.

Step 10 - Calculate annual overnight cool down losses.

- Calculate $(Mcp)_{sys}$ the total thermal capacitance of system components including piping, valves, insulation, and heat transfer fluid. Also, include flash tank or unfired-boiler fluid inventory. Do not include collector absorber tubes, flex hoses or their contained fluid inventories.
- Calculate $(Mcp)_{coll}$ the total thermal capacitance of collector absorber tubes, flex hoses, and their contained fluid inventory.
- Calculate average energy loss overnight from system components based on $(Mcp)_{sys}$ and piping system UA from Step 6.

$$(UA)_{sys} = U_i A_i + U_o A_o$$

$$Q_{o,sys} = \left[1 - e^{-(Mc_p)_{sys}/[(UA)_{sys}\Delta t]}\right](Mc_p)_{sys}(T_s - \bar{T}_{a,n})$$

Use Δt (average overnight cooldown period) = 54,000 sec (15 hours)

- Calculate average energy loss overnight from collector components. (Assume these components cool completely to ambient.)

$$Q_{o,coll} = (Mc_p)_{coll}\,(T_s - \bar{T}_{a,n})$$

- Calculate annual overnight cooldown losses.

$$Q_o = N_{d,c}\,[Q_{o,sys} + Q_{o,coll}]$$

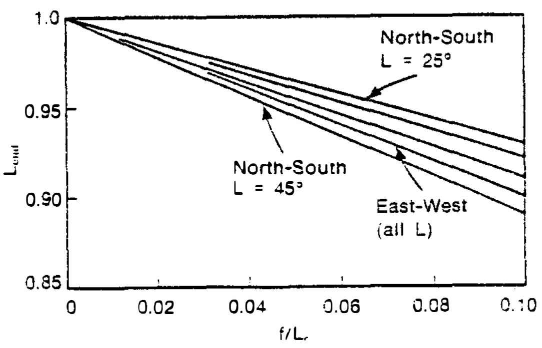

Fig. 7 - End-Loss Factor vs. Collector Focal Length to Collector Length Ratio

where $N_{d,c} = 239 + 0.2\ \overline{I}_b$

Step 11 - Estimate the solar system use factor F_{use}.

- Estimate the annual number of daylight hours that the solar system is likely to be out-of-service due to hardware problems with the solar system. Consider collector reliability, and maintenance of system level components such as circulation pumps and controls.
- Estimate the annual number of daylight hours that the industrial process will be nonoperational, and hence, will not accept solar energy. This time estimate should include scheduled plant shutdowns and unscheduled shutdowns for maintenance based on historical plant data.
- Compute the solar system use factor based on the total expected daytime hours of solar system downtime and industrial process downtime. (Note: 4380 = annual number of daytime hours)

$$F_{use} = 1 - \frac{HR_{\substack{solar\\downtime}} + HR_{\substack{process\\downtime}}}{4380}$$

Step 12 - Calculate annual energy delivery and solar fraction.

- Subtract annual overnight losses (Step 10) from the annual energy collection determined in Step 9.

$$Q_d = Q_c - Q_o$$

- Multiply annual energy total by the use factor estimated in Step 11. This result is the solar system annual energy delivery.
- To obtain that fraction of the process load met by solar energy (neglecting electrical parasitics), divide the annual energy delivered by the annual process load.

$$\text{solar fraction} = \frac{Q_d}{Q_{load}}$$

EXAMPLE CALCULATION

A food processing plant near Denver, Colo. uses 1723 kPa (250 psia) of saturated steam at a rate of 5000 kg/hr (11,023 lb/hr) seven days/week, 24 hr/day. A 2500 m^2 trough MISR system (Alvis, 1983) is being considered to provide some of the process steam. Calculate the expected annual energy delivery of the solar system and the fraction of the annual process load that can be met by the solar system.

Step 1

- $T_s = 205^oC$ (saturation temperature at 250 psia)
  $T_{feed} = 120^oC$
- $L = 39.7^oN$
  $\overline{T}_a = 11^oC$, $\overline{T}_{a,n} = 5^oC$
- Parabolic trough efficiency is given as

$$\eta_c = .80 - .676 \frac{\Delta T}{I} - .334 \left(\frac{\Delta T}{I}\right)^2$$

The preferred efficiency equation, assuming $I_{test} = 1000\ W\ m^{-2}$ is:

$$\eta_c = .80 - .676 \frac{\Delta T}{I} - .000334 \frac{(\Delta T)^2}{I} \ .$$

From this equation both $F'\eta_o$ and $F'U_L$ can be defined.

$$F'\eta_o = .80 \text{ and } F'U_L = .676 + .000334\ \Delta T$$

$$\text{For } \Delta T = T_s - \overline{T}_a = 205^oC - 11^oC = 194^oC,$$

$$F'U_L = .676 + .000334\ (194) = .741\ W\ m^{-2}{}^oC^{-1}.$$

- The available land at the food processing plant is limited to two acres. This land is immediately adjacent to the plant.

Step 2

- The industrial process energy use rate is:

$$\dot{Q}_{load} = \dot{M}_s\ [h_{fg} + c_p\ (T_s - T_{feed})]$$

$$= 5000 \frac{Kg}{hr} \left(\frac{1hr}{3600s}\right) \left[1.92 \times 10^5 \frac{J}{Kg} + 4542 \frac{J}{Kg^oC} (205^oC - 120^oC)\right]$$

$$= 3.203 \times 10^6\ W$$

The maximum collector area $A_{c,max}$ for this energy use rate is:

$$A_{c,max} = \dot{Q}_{load} / [F'\eta_o\ I_{max} - F'U_L(T_s - T_{a,max})] \ .$$

Using $I_{max} = 1100\ W\ m^{-2}$ and $T_{a,max} = 40^oC$;

$$A_{c,max} = 3.203 \times 10^6 / [.8(1100) - .741\ (205 - 40)] = 4227\ m^2$$

- The $A_{c,max}$ value of 4227 m^2 is larger than the MISR collector field area of 2500 m^2. Hence, the 2500 m^2 MISR field is not too large for this industrial process.
- The MISR system under consideration has:
  - a center feed piping layout,
  - fourteen parallel collector rows,
  - two collector drive strings per row,
  - north-south orientation,
  - a total collector field flow rate (Therminol 60) of 17.64 kg s^{-1} (280 gpm),
  - a row-to-row spacing of 6.1 m (20 ft) with a collector aperture width of 2.44 m (8 ft).
- The MISR energy transport system has the following characteristics:
  - Inlet Header, 3-in. sch. 40, 150 m long, 3-in. fiberglass insulation,
  - Outlet Header, 3-in. sch. 40, 130 m long, 3-in. fiberglass insulation,
  - Row-to-row piping, 1.25-in. sch. 40, 180 m long, 1.5-in. fiberglass insulation,
  - Pipe supports every 4.5 m.
  - 28 collector row isolation valves, 1.25-in., insulated body,
  - 5 m^3 expansion tank, 3-in. fiberglass insulation,
  - 18, 3-in. isolation valves, insulated body,
  - 14, 1.25-in. pressure relief valves.

Step 3

- $$\frac{F_R}{F'} = \frac{\dot{M}_c c_p}{A_c F'U_L} \left[1 - \exp - \left(\frac{A_c F'U_L}{\dot{M}_c c_p}\right)\right]$$

$$= \frac{17.64\ (2300)}{2500\ (.741)} \left[1 - \exp - \left(\frac{2500\ (.741)}{17.64\ (2300)}\right)\right] = .9775$$

$$F_R\eta_o = \frac{F_R}{F'} F'\eta_o = .9775\ (.80) = .782$$

$$F_RU_L = \frac{F_R}{F'} F'U_L = .9775\ (.741\ \mathrm{W\ m^{-2}\,{}^\circ C^{-1}}) = .724\ \mathrm{W\ m^{-2}\,{}^\circ C^{-1}}$$

Step 4

- Calculate F_B, the unfired boiler factor.

The MISR system unfired boiler is specified to have a U_bA_b value of 40,000 $\mathrm{W^\circ C^{-1}}$ (75,820 $\mathrm{Btu\ hr^{-1}\,{}^\circ F)^{-1}}$.

$$F_S = F_B = \left[1 + \frac{A_cF_RU_L}{\dot{M}_cc_p\left(e^{U_bA_b/\dot{M}_cc_p}-1\right)}\right]^{-1}$$

$$= \left[1 + \frac{(2500)(.724)}{(17.64)(2300)\ \left(e^{40,000/(17.64\,\cdot\,2300)}-1\right)}\right]^{-1}$$

$$= .974$$

Step 5

- Reflective material samples were placed at the proposed solar site as soon as the site was selected. An average specular reflectance loss of 5% per month has been measured. Since bimonthly concentrator cleaning is anticipated for the solar system, an average optical efficiency loss of 5% is expected over the long term. Because receiver cleaning is a much easier operation than concentrator cleaning, the receiver will be cleaned biweekly and only a 2% loss in average optical efficiency is expected.
- The tested incident angle modifier of the collector at incident angles of 7.5°, 22.5°, 37.5°, 52.5°, and 67.5° are given below.

$K_{7.5}$ = 1.00
$K_{22.5}$ = .99
$K_{37.5}$ = .96
$K_{52.5}$ = .88
$K_{67.5}$ = .65

For north-south troughs at latitudes near 40°, the incident angle weighting factors (from Table 1) are:

$W_{7.5}$ = .35
$W_{22.5}$ = .33
$W_{37.5}$ = .22
$W_{52.5}$ = .10
$W_{67.5}$ = .01

Based on those values, the incident-angle modifier annual correction can now be calculated.

$$\bar{K}_{\tau\alpha} = .35(1.00) + .33(.99) + .22(.96) + .10(.88) + .01(.65)$$

$$= .9824$$

- The effective optical efficiency is:

$$F_R\bar{\eta}_o = .782\ (.95)(.98)(.9824) = .715$$

Step 6

- All energy transport components used in the solar system are given in Table 2 along with their UA values. These UA values are based on data given in references 5 and 8.

$$U_iA_i = 163.2\ \mathrm{W\ {}^\circ C^{-1}}$$

$$U_oA_o = 128.1\ \mathrm{W\ {}^\circ C^{-1}}$$

- $F_R\bar{\eta}'_o = e^{-U_oA_o/\dot{M}_cc_p}$

$$= e^{-128.1/[(17.64)(2300)]}$$

$$= .997$$

$$F_R\bar{\eta}'_o = .997\ (.782) = .780$$

- $$\frac{F_RU'_L}{F_RU_L} = e^{-U_oA_o/\dot{M}_cc_p}\left[e^{-U_iA_i/\dot{M}_cc_p} + \frac{\dot{M}_cc_p}{A_cF_RU_L}\left(e^{U_oA_o/\dot{M}_cc_p} - e^{-U_iA_i/\dot{M}_cc_p}\right)\right]$$

$$= .997\left[e^{-163.2/[(17.64)(2300)]} + \frac{17.64\ (2300)}{2500\ (.724)}\left(e^{128.11/[(17.64)(2300)]} - e^{-163.2/[(17.64)(2300)]}\right)\right]$$

$$= 1.153$$

$$F_RU'_L = 1.153\ (.724) = .835\ \mathrm{W\ m^{-2}\,{}^\circ C^{-1}}$$

Step 7

- Intensity Ratio $= \dfrac{F_RU'_L\ (T_s - \bar{T}_a)}{F_R\bar{\eta}'_o\ \bar{I}_b}$

$$= \frac{.835\ \mathrm{W\ m^{-2}\,{}^\circ C^{-1}}\ (205^\circ\mathrm{C} - 11^\circ\mathrm{C})}{.780\ (525\ \mathrm{W\ m^{-2}})} = 0.396$$

- Using a hand calculator rather than the graphical technique:

$$\frac{\bar{\dot{q}}_c}{F_SF_R\bar{\eta}'_o\ (\bar{I}_b + 50)} = .8810 - .8117\ (0.396)$$

Table 1. Incident Angle Modifier Annual Correction Weighting Factor

Weighting Factor	East-West All Latitudes	North-South L=25°	L=30°	L=35°	L=40°	L=45°	L=50°
$W_{7.5}$	0.24	0.47	0.45	0.43	0.35	0.29	0.26
$W_{22.5}$	0.23	0.30	0.29	0.28	0.33	0.38	0.40
$W_{37.5}$	0.22	0.16	0.17	0.18	0.22	0.25	0.26
$W_{52.5}$	0.20	0.08	0.10	0.12	0.10	0.07	0.07
$W_{67.5}$	0.15	0.00	0.00	0.00	0.01	0.02	0.02

Table 2. Energy Transport System Component Loss Coefficients

Quantity	Component	$UA (W °C^{-1})$
Inlet Side Components		
150m	3 in. sch. 40 piping with 3 in. fiberglass insulation	54.2
90m	1.25 in. sch. 40 piping with 1.5 in. fiberglass insulation	31.4
1	Unfired Boiler with 3 in. fiberglass insulation	11.3
1	Circulation pump, insulated, with seal cooling	13.8
1	Expansion tank, 3 in. fiberglass insulation	2.8
33	Pipe supports for 3 in. piping using calcium silicate	5.3
14	Pipe supports for 1.25 in piping using calcium silicate	4.2
1	Pipe Anchor	0.6
28	Flexible hoses, 1.42m long	30.8
10	Insulated hand valves for 3 in. piping	5.7
14	Insulated hand valves for 1.25 in. piping	3.1
		$U_iA_i = 163.2 W °C^{-1}$
Outlet Side Components		
130m	3 in. sch. 40 piping with 3 in. fiberglass insulation	45.4
90m	1.25 in. sch. 40 piping with 1.5 in. fiberglass insulation	31.4
30	Pipe supports for 3 in. piping using calcium silicate	4.9
14	Pipe supports for 1.25 in. piping using calcium silicate	4.2
1	Pipe anchor	0.6
28	Flexible hoses, 1.42m long	30.8
8	Insulated hand valves for 3 in. piping	4.6
14	Insulated hand valves for 1.25 in. piping	3.1
14	Insulated pressure relief valves	3.1
		$U_oA_o = 128.1 W °C^{-1}$

$$+.3130\ (0.396)^2 - .003919\ (39.7)$$

$$+ .003864\ (39.7)(0.396) - .001484\ (39.7)(0.396)^2 = .5046$$

- $\overline{\dot{q}}_c = F_S F_R \overline{\eta}'_o\ (I_b + 50)\ (.5046)$

$$= .974\ (.780)\ (525 + 50\ W\ m^{-2})\ (.5046)$$

$$= 239\ W\ m^{-2}$$

Step 3

- GCR = 8/20 = .40
- $A_g = A_c/GCR = 2500\ m^2\ (.40 = 6250\ m^2)$
- 6250 m^2 is just over 1.5 acres. Since two acres is available, the MISR system will fit in the space allocated.
- From Fig. 6 (for a latitude of 39.7°), F_{shade} is 0.95).
- The field shading loss factor is calculated based on 14 rows.

$$F_{shade,field} = \frac{1 + (14 - 1)\ .95}{14} = .954$$

- $\overline{\dot{q}}_c = .954\ (239\ W\ m^{-2}) = 228\ W\ m^{-2}$
- Four 6.1 m long concentrators are mounted adjacent to each other on each side of the drive assembly of each row. Hence, $L_c = 24.4$ m. The focal length of ech concentrator is 0.61 m. For $L_c/f = 24.4/0.61 = 40$, Fig. 7 indicates $L_{end} = .98$.
- $\overline{\dot{q}}_c = 0.98\ (228\ W\ m^{-2}) = 223\ W\ m^{-2}$

Step 9

- $\overline{\dot{Q}}_c = \overline{\dot{q}}_c\ A_c = 223\ W\ m^{-2}\ (2500\ m^2)$

$$= 557500\ W$$

- Converting to Joules:

  $557500\ (1.5768 \times 10^7) = 8.791 \times 10^{12}\ J$

Step 10

- The total thermal capacitance of the energy transport system is $11.8 \times 10^6\ J\ °C^{-1}$ as given in Table 3.

$$(Mc_p)_{sys} = 11.8 \times 10^6\ J\ °C^{-1}$$

- The total thermal capacitance of the collector system is $3.64 \times 10^6\ J\ °C^{-1}$ as given in Table 4.

$$(Mc_p)_{coll} = 3.64 \times 10^6\ J\ °C^{-1}$$

- $(UA)_{sys} = U_iA_i + U_oA_o$

$$= 163.2 + 128.1 = 291.3\ W\ °C^{-1}$$

$$Q_{o,sys} = \left[1 - e^{-(Mc_p)_{sys}/[(UA)_{sys}\Delta t]}\right] (Mc_p)_{sys}(T_s - \overline{T}_{a,n})$$

$$= \left[1 - e^{-11.8 \times 10^6/[291.3(54000)]}\right] 11.8 \times 10^6(205 - 5)$$

$$= 1.245 \times 10^9\ J$$

- $Q_{o,coll} = (Mc_p)_{coll}\ (T_s - \overline{T}_{a,n})$

$$= (3.64 \times 10^6\ J\ °C^{-1})(205° - 5°C)$$

Table 3. Energy Transport System Thermal Capacitance

Quantity	Component	MCp (J^oC^{-1})
1	Pump	0.06×10^6
280m	76mm (3 in.) piping with 76mm (3 in.) insulation	5.32×10^6
180m	32mm (1.25 in.) piping with 38mm (1.5 in.) insulation	0.94×10^6
1	Unfired boiler with 76mm (3 in.) insulation	4.09×10^6
28	Insulated hand valves for 1.25 in. piping	$.16 \times 10^6$
21	Insulated hand valves for 3 in. piping	$.32 \times 10^6$
14	Pressure relief valves	$.16 \times 10^6$
1	Expansion tank, insulated	$.78 \times 10^6$
		$(MCp)_{sys} = 11.8 \times 10^6 J^oC^{-1}$

Table 4. Collector System Thermal Capacitance

Quantity	Component	MCp (J^oC^{-1})
1024m	32mm (1.25 in.) absorber tube, including contained fluid	3.27×10^6
56	Flexible hoses, 1.42m long, including contained fluid	$.37 \times 10^6$
		$(MCp)_{coll} = 3.64 \times 10^6 J^oC^{-1}$

$$= 7.28 \times 10^8 \text{ J}$$

- $N_{d,c} = 239 + 0.2 \overline{I_b}$

$$= 239 + 0.2\ (525) = 344 \text{ days}$$

$$Q_o = 344\ [1.245 \times 10^9 \text{ J} + 7.28 \times 10^8 \text{ J}]$$

$$= 6.79 \times 10^{11} \text{ J}$$

Step 11

- Considering the past reliability of trough systems and the availability of an on-site maintenance crew 24 hr/day, it is expected that the entire collector system will rarely be out-of-service. Four days (48 daylight hours) of system downtime is estimated. Additionally, one drive string (out of 28) is estimated to be down two days (24 daylight hours) of each month or 288 daylight hours per year. Because there are 28 drive strings, the entire collector system can be equivalently considered to be down 10.3 hours (= 288/28 hrs). Hence, the total equivalent solar system downtime is 58.3 (= 48 + 10.3) daylight hours.

  HR solar downtime = 58.3 hr/yr.

- The food processing plant has a one week holiday shutdown in December and a five day shutdown in early spring. This amounts to 144 lost daylight hours per year. HR process downtime = 144 hr/yr.

- $F_{use} = 1 - \dfrac{58.3 + 144}{4380} = 0.954$

Step 12

- Subtract annual overnight losses.

$$Q_d = Q_c - Q_o$$

$$= 8.791 \times 10^{12} \text{ J} - 6.79 \times 10^{11} \text{ J}$$

$$= 8.112 \times 10^{12} \text{ J}$$

- Multiply by the solar system use factor.

$$Q_d = (.954)(8.112 \times 10^{12} \text{ J})$$

$$= 7.739 \times 10^{12} \text{ J } (7.336 \times 10^3 \text{ MBtu})$$

- Calculate solar fraction.

$$Q_{load} = \dot{Q}_{load} \left(24 \frac{hr}{day}\right)\left(365 - 12 \frac{day}{yr}\right)\left(\frac{3600s}{hr}\right)$$

For $\dot{Q}_{load} = 3.203 \times 10^6$ W ,

$$\dot{Q}_{load} = 9.769 \times 10^{13} \text{ J yr}^{-1}$$

$$\text{solar fraction} = \frac{Q_d}{Q_{load}} = \frac{7.739 \times 10^{12} \text{ J yr}^{-1}}{9.769 \times 10^{13} \text{ J yr}^{-1}}$$

$$= 0.079\ (7.9\%)$$

A detailed hour-by-hour SOLIPH computer run was made as a comparison to the step-by-step procedure result. The Denver TMY tape was used as the weather/irradiation data base. The annual energy delivery result was 7.637×10^{12} J yr^{-1}. This result compares very closely (within 2%) of the step-by-step procedure result and attests to the accuracy of the simplified energy calculation method.

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