TYPE 566: GLAZED BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEM (INTERACTS WITH ZONE AIR TEMPERATURE)

This component is intended to model a glazed solar collector which has the dual purpose of creating power from embedded photovoltaic (PV) cells and providing heat to an air stream passing beneath the absorbing PV surface. The waste heat rejected to the air stream is useful for two reasons; 1) it cools the PV cells allowing higher power conversion efficiencies and 2) it provides a source of heat for many possible low-grade temperature applications including heating of room air. This model is intended to operate with simple building models that can provide the temperature of the zone air on the back-side of the collector and possibly provide an estimate of the radiant temperature for back-side radiation calculations (the room air temperature may be used as a suitable estimate of the radiant temperature if surface temperatures are not available).

The model allows for the user to choose between two methods of handling the off-normal solar radiation effects. The model allows the user three options on specifying how the cell temperature, and the incident solar radiation affect the PV efficiency. The cells are assumed to be operating at their maximum power point condition; implying that the voltage and current are not calculated by the model.

The thermal model of this collector relies on algorithms supplied by the classic "Solar Engineering of Thermal Processes" textbook by Duffie and Beckman.

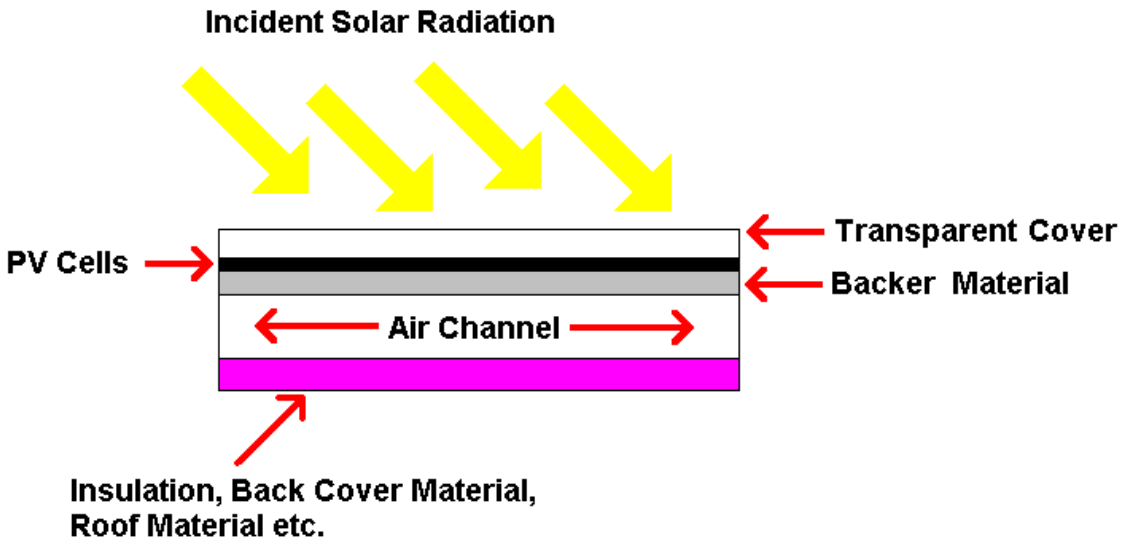


Figure 1 –Collector Schematic

Nomenclature

β	- slope of the collector surface
μ_{fluid}	- the viscosity of the fluid flowing through the channel
η	- efficiency
θ	- angle of incidence of solar radiation
ρ_g	- ground reflectance
ρ_{fluid}	- the density of the fluid in the flow channel
$\tau\alpha$	- transmittance-absorptance product for the solar collector
ε_{back}	- emissivity of the back surface of the collector (towards zone)
ε_{cover}	- emissivity of the cover surface of the collector (towards sky)
ε_1	- emissivity of the bottom side of the upper surface of the air channel
ε_2	- emissivity of the top side of the lower surface of the air channel
σ	- Stefan-Boltzmann constant
ν_{fluid}	- the viscosity of the fluid in the flow channel
ΔT_{plates}	- the temperature difference between the plates defining the flow channel
Area	- area (top) of the solar collector; this can be either gross area or net area but should be consistent with the provided loss coefficients.
b_0	- linear incidence angle modifier constant
Cp_{fluid}	- the specific heat of the fluid in the flow channel
D_h	- the hydraulic diameter of the flow channel
Eff_G	- modifier for PV efficiency as a function of incident solar radiation
Eff_T	- modifier for PV efficiency as a function of cell temperature
g	- the acceleration due to gravity
G_{bT}	- incident beam radiation on the tilted cover surface
G_d	- incident sky diffuse radiation on the tilted cover surface
G_h	- horizontal diffuse radiation
G_{ref}	- reference solar radiation at which the standard PV efficiency is given
G_T	- total incident solar radiation on the collector surface
$h_{conv,back}$	- convective heat transfer coefficient from the back of the collector to the zone air
$h_{conv,top}$	- convective heat transfer coefficient from the top of the cover surface to the ambient air
h_{fluid}	- heat transfer coefficient from the fluid in the flow channels to the walls of the flow channel (evaluated at the mean fluid temperature)
$h_{rad,1-2}$	- the linearized radiation heat transfer coefficient from the top surface of the air channel to the bottom surface of the air channel
$h_{rad,back}$	- radiative heat transfer coefficient from the back of the collector to the zone radiant temperature
$h_{rad,top}$	- radiative heat transfer coefficient from the top of the cover surface to the sky
IAM	- incidence angle modifier
k_{cover}	- thermal conductivity of the cover material
k_{fluid}	- thermal conductivity of the fluid in the flow channel
L	- the length of the collector along the flow direction
$\dot{m}$	- the flow rate of fluid through the channel
Nu	- the Nusselt number for the fluid in the flow channel
Pr	- the Prandtl number for the fluid in the flow channel
q_u''	- net rate at which energy is added to the flow stream by the collector per unit area
$Q_{absorbed}$	- rate at which energy is absorbed by the collector

$Q_{loss,top,conv}$ - rate at which energy is lost to the ambient through convection off the cover
$Q_{loss,top,rad}$ - rate at which energy is lost to the sky through radiation off the cover
$Q_{loss,back,conv}$ - rate at which energy is lost to the zone through convection off the back of the collector
$Q_{loss,back,rad}$ - rate at which energy is lost to the zone through radiation off the back of the collector
Q_u - net rate at which energy is added to the flow stream by the collector
Ra - the Rayleigh number of the fluid in the channel
Re - the Reynolds number of the fluid flowing through the channel
R_1 - resistance to heat transfer from the top of the cover surface to the PV cells (typically the resistance of the cover material)
R_2 - resistance to heat transfer from the surface of the PV cells to the upper surface of the flow channel
R_3 - resistance to heat transfer from the lower surface of the flow channel to the back-side of the collector
S - the absorbed solar radiation minus any PV power production
Slope - the slope of the flow channel off of horizontal (vertical =90)
Spacing - the spacing between the plates defining the flow channel
T_1 - temperature of the upper air-channel surface
T_2 - temperature of the lower air-channel surface
T_3 - temperature of the back surface of the collector (zone air / collector interface)
T_{amb} - ambient temperature for convective losses from the cover surface
T_{back} - temperature of the air behind the collector (zone air)
$T_{back,rad}$ - temperature of the surroundings behind the collector for back-side radiation heat transfer
T_{Cover} - temperature of the outer surface of the transparent cover material
T_{fluid} - local temperature of the fluid flowing through the solar collector
$T_{fluid,in}$ - temperature of the fluid flowing into the solar collector
$T_{fluid,out}$ - temperature of the fluid flowing out of the solar collector
T_{PV} - temperature of the absorbing surface of the PV cells
T_{ref} - reference temperature at which the standard PV efficiency is given
T_{sky} - sky temperature for radiative losses from the cover surface
TH_{cover} - thickness of the cover material
$\overline{T}_{plates}$ - the average temperature of the plates defining the flow channel
$\overline{T}_{fluid}$ - mean fluid temperature
W - the width of the collector
$X_{Cell\ Temp}$ - multiplier for the PV cell efficiency as a function of the cell temperature
$X_{Radiation}$ - multiplier for the PV cell efficiency as a function of the incident radiation
y - a variable indicating the direction of flow through the collector (y=L is the collector outlet)

Subscripts

b - beam radiation
d - diffuse radiation
g - ground diffuse
h - total horizontal
n - normal incidence
nominal - refers to the reference conditions
s - sky diffuse

t - total (beam + diffuse)

Mathematical Description:

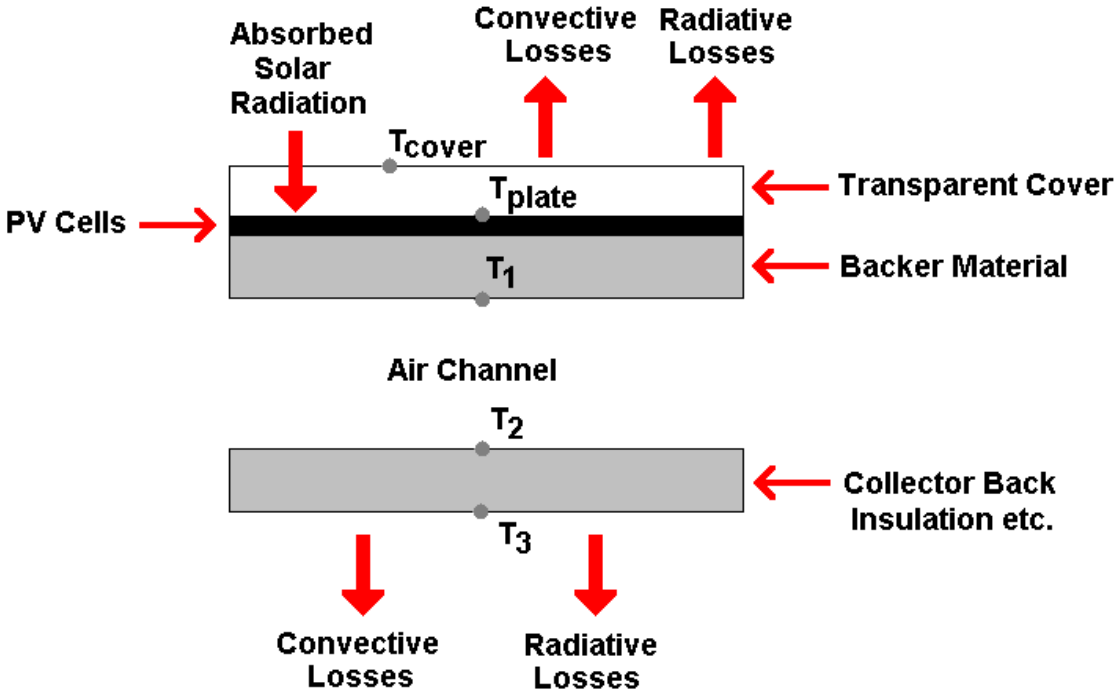


Figure 2 - Collector Definitions

An energy balance on the cover surface at any point along the surface shows the following relationship:

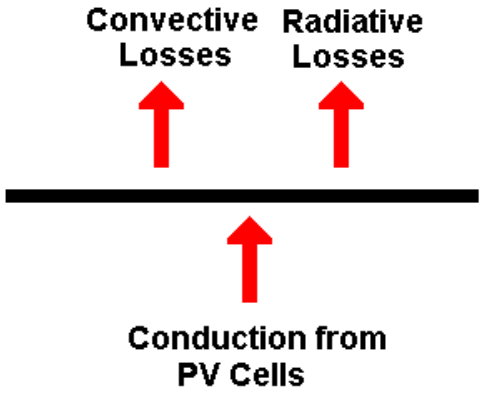


Figure 3: Cover Surface Energy Balance

$$\frac{\left(T_{PV} - T_{Cover}\right)}{R_1} = h_{conv,top}\left(T_{Cover} - T_{amb}\right) - h_{rad,top}\left(T_{Cover} - T_{sky}\right) \qquad \text{(Eq. 566.1)}$$

where:

$$h_{rad,top} = \varepsilon_{Cover}\,\sigma\left(T_{Cover} + T_{sky}\right)\left(T_{Cover}^{\ 2} + T_{sky}^{\ 2}\right) \qquad \text{(Eq. 566.2)}$$

$$R_1 = \frac{TH_{Cover}}{k_{Cover}} \qquad \text{(Eq. 566.3)}$$

An energy balance on the PV surface (absorbing surface) at any point along the surface shows the following relationship:

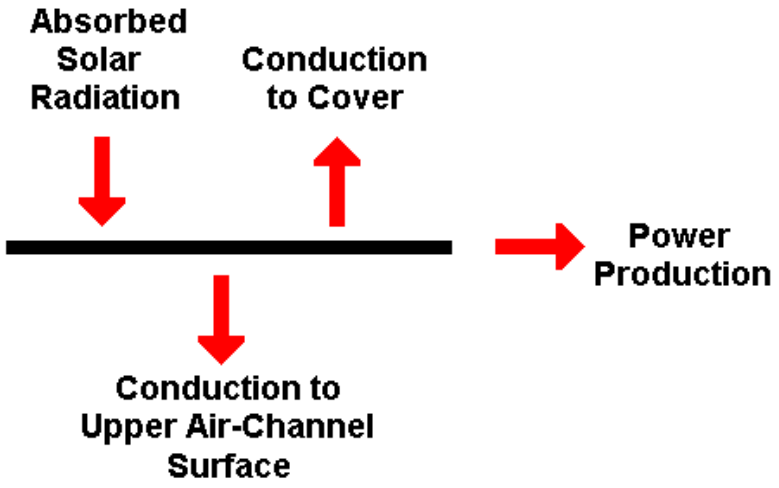


Figure 4: Absorbing Surface Energy Balance

$$S = \frac{\left(T_{PV} - T_{Cover}\right)}{R_1} + \frac{\left(T_{PV} - T_1\right)}{R_2} \qquad \text{(Eq. 566.4)}$$

S is the absorbed solar radiation minus any PV power production. To account for off-normal solar radiation effects, the transmittance-absorptance product at normal incidence is multiplied by the following term in order to get the transmittance-absorptance at other incidence angles. This term is referred to as the incidence angle modifier (IAM).

$$IAM = \frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{G_{bT}\,\frac{(\tau\alpha)_b}{(\tau\alpha)_n} + G_d\,\frac{(1+\cos\beta)}{2}\,\frac{(\tau\alpha)_s}{(\tau\alpha)_n} + G_h\,\rho_g\,\frac{(1-\cos\beta)}{2}\,\frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{G_T} \qquad \text{(Eq. 566.5)}$$

This model allows the user to choose two different modes for calculating the incidence angle modifiers. In mode 1, the user provides a linear incidence angle modifier constant (b0) used to calculate the IAM as well at the transmittance absorptance product at normal incidence $(\tau\alpha)_n$:

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) \quad \text{(Eq. 566.6)}$$

In mode 2, the user enters parameters about the cover material, as well as the absorptance of the PV surface, and the model uses the TALF subroutine (refer to section 3.4.3 of the TRNSYS manual) to calculate the transmittance-absorptance product at normal incidence.

The incidence angle modifiers for both sky and diffuse radiation are determined by defining equivalent incidence angles for beam radiation that give the same transmittance as for diffuse radiation (Duffie and Beckman). The effective angles for sky diffuse and ground reflected radiation are:

$$\theta_{sky} = 59.68 - 0.1388\,\beta + 0.001497\,\beta^2 \quad \text{(Eq. 566.7)}$$

$$\theta_{ground} = 90.0 - 0.5788\,\beta + 0.002693\,\beta^2 \quad \text{(Eq. 566.8)}$$

The efficiency of the PV cells is typically a function of the cell temperature and the incident solar radiation. This model allows the user to choose from one of three PV efficiency modes.

In the first mode, the user enters the PV efficiency at reference conditions, provides the reference conditions and also provides linear modifying factors for the efficiency. The efficiency is then calculated as:

$$\eta_{PV} = \eta_{nominal}\ X_{CellTemp}\ X_{Radiation} \quad \text{(Eq. 566.9)}$$

where:

$$X_{CellTemp} = 1 + Eff_T\left(T_{PV} - T_{ref}\right) \quad \text{(Eq. 566.10)}$$

$$X_{Radiation} = 1 + Eff_G\left(G_T - G_{ref}\right) \quad \text{(Eq. 566.11)}$$

In the second mode, the user must provide a data file containing the efficiency of the PV cells as a function of the cell temperature and the incident solar radiation. The data must be provided in a special formatted ASCII text file which can be read by TRNSYS. A simple example file is provided with purchase (**`Sample_PV_Efficiency.dat`**) and a copy of this simple file is included at the end of this documentation.

$$\eta_{PV} = f(Cell\ Temperaure\ \&\ Incident\ Radiation) \quad \text{(Eq. 566.12)}$$

In the third mode, the user provides the efficiency as an INPUT to the model (provides great flexibility to calculate the efficiency as a function of any subset of variables)

$$\eta_{PV} = An\ Input\ to\ the\ Model \qquad \text{(Eq. 566.13)}$$

With these definitions S, the net absorbed solar radiation from equation 566.4, can be determined as:

$$S = (\tau\alpha)_n\ IAM\ G_T\ (1-\eta_{PV}) \qquad \text{(Eq. 566.14)}$$

An energy balance on the upper air channel surface at any point along the surface shows the following relationship:

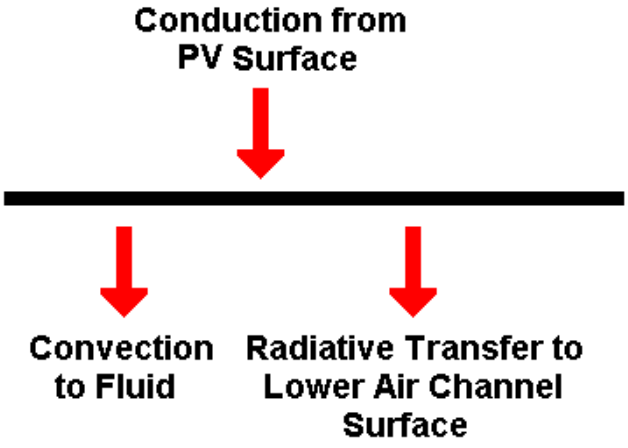


Figure 5: Upper Air Channel Surface Energy Balance

$$\frac{(T_{PV}-T_1)}{R_2} = h_{fluid}(T_1 - T_{fluid}) - h_{rad,1\to2}(T_1 - T_2) \qquad \text{(Eq. 566.15)}$$

An energy balance on the air flowing through the collector at any point shows the following relationship:

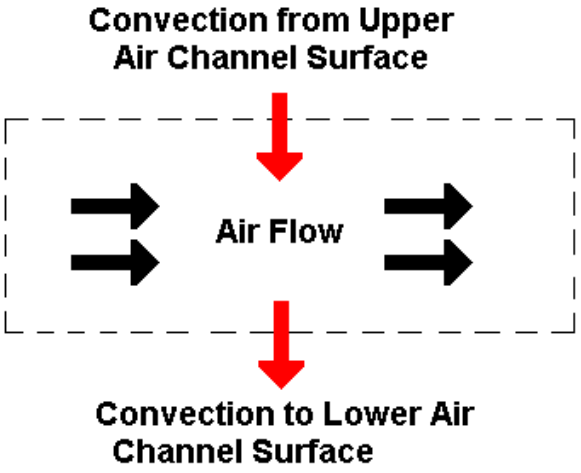


Figure 6: Fluid Energy Balance

$$q''_u = h_{fluid}\left(T_1 - T_{fluid}\right) - h_{fluid}\left(T_{fluid} - T_2\right) \qquad \text{(Eq. 566.16)}$$

An energy balance on the lower air channel surface at any point along the surface shows the following relationship:

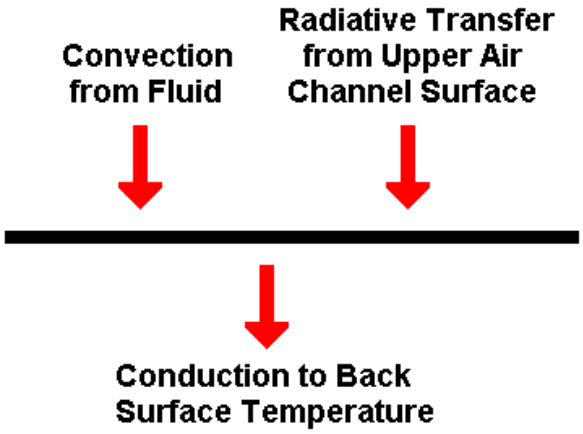


Figure 7: Lower Air Channel Surface Energy Balance

$$h_{fluid}\left(T_{fluid} - T_2\right) + h_{rad,1\to 2}\left(T_1 - T_2\right) = \frac{\left(T_2 - T_3\right)}{R_3} \qquad \text{(Eq. 566.17)}$$

where:

$$h_{rad,1\to 2} = \frac{\sigma\left(T_1^{\,2} + T_2^{\,2}\right)\left(T_1 + T_2\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \text{(Eq. 566.18)}$$

An energy balance on the back collector surface at any point along the surface shows the following relationship:

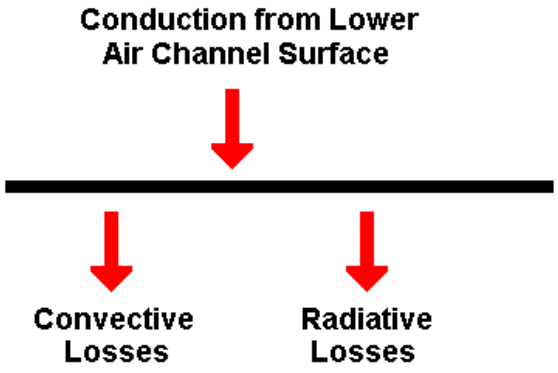


Figure 8: Collector Back Surface Energy Balance

$$0 = \frac{\left(T_2 - T_3\right)}{R_3} - h_{conv,back}\left(T_3 - T_{back}\right) - h_{rad,back}\left(T_3 - T_{back,rad}\right) \qquad \text{(Eq. 566.19)}$$

where:

$$h_{rad,back} = \varepsilon_{back}\,\sigma\left(T_3 + T_{back,rad}\right)\left(T_3^{\,2} + T_{back,rad}^{\;\;2}\right) \qquad \text{(Eq. 566.20)}$$

Solving the six energy balance equations (Equations 566.1, 566.4, 566.15, 566.16, 566.17 and 566.19) for the collector useful energy gain as a function of the local fluid temperature, we find:

$$q''_u = T_{fluid}\left(-2h_{fluid} + \frac{R_2\ h_{fluid}^{\ 2}}{m} + \frac{h_{fluid}^{\ 2}}{j} + \frac{2\ R_2\ h_{fluid}^{\ 2}\ h_{rad,1\to2}}{m\ j} + \frac{R_2\ h_{fluid}^{\ 2}\ h_{rad,1\to2}^{\ 2}}{m\ j^2}\right)$$
$$+\frac{h_{fluid}\ h_{conv,back}T_{back}}{j\ H'} + \frac{h_{fluid}\ h_{rad,back}T_{back,rad}}{j\ H'} + \frac{h_{fluid}\ S}{G'\ m} + \frac{h_{fluid}\ h_{conv,top}T_{amb}}{F'\ G'\ m} + \frac{h_{fluid}\ h_{rad,top}T_{sky}}{F'\ G'\ m}$$
$$+\frac{h_{fluid}\ R_2\ h_{rad,1\to2}\ h_{conv,back}T_{back}}{H'\ j\ m} + \frac{h_{fluid}\ R_2\ h_{rad,1\to2}\ h_{rad,back}T_{back,rad}}{H'\ j\ m} + \frac{h_{fluid}\ h_{rad,1\to2}\ S}{G'\ j\ m} \qquad \text{(Eq. 566.21)}$$
$$+\frac{h_{fluid}\ h_{rad,1\to2}\ h_{conv,top}T_{amb}}{G'\ F'\ j\ m} + \frac{h_{fluid}\ h_{rad,1\to2}\ h_{rad,top}T_{sky}}{G'\ F'\ j\ m} + \frac{h_{fluid}\ R_2\ h_{rad,1\to2}^{\ 2}\ h_{conv,back}T_{back}}{H'\ j^2\ m}$$
$$+\frac{h_{fluid}\ R_2\ h_{rad,1\to2}^{\ 2}\ h_{rad,back}T_{back,rad}}{H'\ j^2\ m}$$

where:

$$F' = h_{rad,top}R_1 + h_{conv,top}R_1 + 1 \qquad \text{(Eq. 566.22)}$$

$$G' = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_1\ F'} \qquad \text{(Eq. 566.23)}$$

$$H' = 1 + R_3\ h_{conv,back} + R_3\ h_{rad,back} \qquad \text{(Eq. 566.24)}$$

$$j = h_{fluid} + h_{rad,1\to2} + \frac{1}{R_3} - \frac{1}{H'\ R_3} \qquad \text{(Eq. 566.25)}$$

$$m = 1 - \frac{1}{R_2\ G'} + R_2\ h_{fluid} + R_2\ h_{rad,1\to2} - \frac{R_2\ h_{rad,1\to2}^{\ 2}}{j} \qquad \text{(Eq. 566.26)}$$

Note that the above formulation assumes that the convection coefficients from the air to the upper and lower surfaces of the air channel are identical.

The fluid convection correlations are based on the Reynolds number of the fluid flowing through the flow channel:

$$\mathrm{Re} = \frac{4\ \dot{m}}{\pi\ D_h\ \mu} \qquad \text{(Eq. 566.27)}$$

where the hydraulic diameter is calculated as the cross-sectional area of the flow channel divided by the perimeter of the flow channel.

If the Reynolds number is zero (no flow through the channel), the Nusselt number is based on a natural convection heat transfer correlation (all temperature in degrees Kelvin) :

$$Nu = 1 + 1.44\left[1 - \frac{1708\left(\sin^{1.6}\left(1.8\ Slope\right)\right)}{Ra\cos\left(Slope\right)}\right] * Max\left[0, \left(1 - \frac{1708}{Ra\cos\left(Slope\right)}\right)\right] + Max\left[0, \left(\left(\frac{Ra\cos\left(Slope\right)}{5830}\right)^{1/3} - 1\right)\right] \quad \text{(Eq. 566.28)}$$

where:

$$Ra = Max\left[1, \left(\frac{g\ \Delta T_{plates}\ Spacing^3}{\overline{T}_{plates}\ \upsilon_{fluid}\ \alpha_{fluid}}\right)\right] \quad \text{(Eq. 566.29)}$$

$$\alpha_{fluid} = \frac{k_{fluid}}{\rho_{fluid}\ Cp_{fluid}} \quad \text{(Eq. 566.30)}$$

If the flow through the channel is laminar (Reynolds number < 2300) then a constant surface temperature heat transfer correlation is utilized:

$$Nu = 3.66 \quad \text{(Eq. 566.31)}$$

If the flow through the channel is turbulent (Reynolds number > 2300) then the Dittus Boelter heat transfer correlation is utilized:

$$Nu = 0.023\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{n} \quad \text{(Eq. 566.32)}$$

The exponent in Equation 566.32 (n) is set to 0.4 for heating (plates warmer than the fluid) and to 0.3 for cooling (plates cooler than the fluid).

The fluid convection coefficient can then be calculated from knowledge of the Nusselt number:

$$h_{fluid} = \frac{Nu\ k_{fluid}}{D_h} \quad \text{(Eq. 566.33)}$$

An energy balance taken around a differential section of fluid moving through the collector (in the y-direction) can be written as:

$$\dot{m}\,C_p\,\frac{dT_{fluid}}{dy} \quad - W\,q''_u = 0 \qquad \text{(Eq. 566.34)}$$

Subbing equation 566.21 into equation 566.34 we find:

$$\frac{dT_{fluid}}{dy} = \left(\frac{W}{\dot{m}\,C_p}\right) a\,T_{fluid} + \left(\frac{W}{\dot{m}\,C_p}\right) b \qquad \text{(Eq. 566.35)}$$

where:

$$a = \left(-2\,h_{fluid} + \frac{R_2\ h_{fluid}^{\ 2}}{m} + \frac{h_{fluid}^{\ 2}}{j} + \frac{2\,R_2\ h_{fluid}^{\ 2}\ h_{rad,1\to2}}{m\ j} + \frac{R_2\ h_{fluid}^{\ 2}\ h_{rad,1\to2}^{\ 2}}{m\ j^2} \right) \qquad \text{(Eq. 566.36)}$$

$$b = \frac{h_{fluid}\ h_{conv,back} T_{back}}{j\ H'} + \frac{h_{fluid}\ h_{rad,back} T_{back,rad}}{j\ H'} + \frac{h_{fluid}\ S}{G'\ m} + \frac{h_{fluid}\ h_{conv,top} T_{amb}}{F'\ G'\ m} + \frac{h_{fluid}\ h_{rad,top} T_{sky}}{F'\ G'\ m}$$
$$+ \frac{h_{fluid}\ R_2\ h_{rad,1\to2}\ h_{conv,back} T_{back}}{H'\ j\ m} + \frac{h_{fluid}\ R_2\ h_{rad,1\to2}\ h_{rad,back} T_{back,rad}}{H'\ j\ m} + \frac{h_{fluid}\ h_{rad,1\to2}\ S}{G'\ j\ m}$$
$$+ \frac{h_{fluid}\ h_{rad,1\to2}\ h_{conv,top} T_{amb}}{G'\ F'\ j\ m} + \frac{h_{fluid}\ h_{rad,1\to2}\ h_{rad,top} T_{sky}}{G'\ F'\ j\ m} + \frac{h_{fluid}\ R_2\ h_{rad,1\to2}^{\ 2}\ h_{conv,back} T_{back}}{H'\ j^2\ m} \qquad \text{(Eq. 566.37)}$$
$$+ \frac{h_{fluid}\ R_2\ h_{rad,1\to2}^{\ 2}\ h_{rad,back} T_{back,rad}}{H'\ j^2\ m}$$

If we assume that a and b are independent of position in the collector along the y-direction, we can integrate equation 566.35 from zero to y and find the local temperature solution:

$$T_{fluid}(y) = \left(T_{fluid,in} + \frac{b}{a}\right) \exp\left(\frac{W}{\dot{m}\,C_p} a\,y\right) - \frac{b}{a} \qquad \text{(Eq. 566.38)}$$

If we let y = L, the collector outlet temperature can be calculated as:

$$T_{fluid,out} = \left(T_{fluid,in} + \frac{b}{a}\right) \exp\left(-\frac{Area\ a}{\dot{m}\,C_p}\right) - \frac{b}{a} \qquad \text{(Eq. 566.39)}$$

The mean fluid temperature can be found by integrating the fluid temperature with respect to y and dividing by the flow length (equation 6.9.1 of Duffie and Beckman):

$$\overline{T}_{fluid} = \frac{1}{L}\int_0^L T_{fluid}(y)\, dy \qquad \text{(Eq. 566.40)}$$

Using equation 566.38 and 566.40 and solving the differential equation we find:

$$\overline{T}_{fluid} = \left(\frac{T_{fluid,in} + \frac{b}{a}}{\frac{Area\ \ a}{\dot{m}\, C_p}} \right) \exp\left(\frac{Area\ \ a}{\dot{m}\, C_p}\right) \quad - \left(\frac{T_{fluid,in} + \frac{b}{a}}{\frac{Area\ \ a}{\dot{m}\, C_p}} \right) \quad - \frac{b}{a} \qquad \text{(Eq. 566.41)}$$

Using equation 566.39, and knowing the collector fluid inlet temperature, we can find the collector useful energy gain as:

$$Q_u = \dot{m}\, C_p \left(T_{fluid,out} - T_{fluid,in} \right) \qquad \text{(Eq. 566.42)}$$

Using the six energy balance equations on the various collector surfaces (Equations 566.1, 566.4, 566.15, 566.16, 566.17 and 566.19), we can derive an expression for the upper air channel mean surface temperature as a function of the mean fluid temperature and other known quantities:

$$\overline{T}_1 = \frac{S}{m\, G'} + \frac{h_{conv,top} T_{amb}}{m\, G' F'} + \frac{h_{rad,top} T_{sky}}{m\, G' F'} + \frac{R_2\ h_{fluid} \overline{T}_{fluid}}{m} + \frac{R_2\ h_{rad,1\to 2} h_{fluid} \overline{T}_{fluid}}{m\ j} + \frac{R_2\ h_{rad,1\to 2} h_{conv,back} T_{back}}{m\ j\ H'} + \frac{R_2\ h_{rad,1\to 2} h_{rad,back} T_{back,rad}}{m\ j\ H'} \qquad \text{(Eq. 566.43)}$$

Using the six energy balance equations on the various collector surfaces (Equations 566.1, 566.4, 566.15, 566.16, 566.17 and 566.19), we can derive an expression for the lower air channel mean surface temperature as a function of the upper air channel mean surface temperature, the mean fluid temperature, and other known quantities:

$$\overline{T}_2 = \frac{h_{rad,1\to 2} \overline{T}_1}{j} + \frac{h_{fluid} \overline{T}_{fluid}}{j} + \frac{h_{conv,back} T_{back}}{j\ H'} + \frac{h_{rad,back} T_{back,rad}}{j\ H'} \qquad \text{(Eq. 566.44)}$$

Again using the six energy balance equations on the various collector surfaces, we can derive an expression for the collector back surface temperature as a function of the lower air channel mean surface temperature and other known quantities:

$$\overline{T}_3 = \frac{\overline{T}_2}{H'} + \frac{R_3\ h_{conv,back} T_{back}}{H'} + \frac{R_3\ h_{rad,back} T_{back,rad}}{H'} \quad \text{(Eq. 566.45)}$$

Using the same approach we can derive an expression for the PV temperature (absorbing surface) as a function of known variables:

$$\overline{T}_{PV} = \frac{S}{G'} + \frac{h_{conv,top} T_{amb}}{G'F'} + \frac{h_{rad,top} T_{sky}}{G'F'} + \frac{\overline{T}_1}{G'R_2} \quad \text{(Eq. 566.46)}$$

Finally we can derive an expression for the cover surface temperature as a function of known variables:

$$\overline{T}_{Cover} = \frac{\overline{T}_{PV}}{F'} + \frac{R_1\ h_{conv,top} T_{amb}}{F'} + \frac{R_1\ h_{rad,top} T_{sky}}{F'} \quad \text{(Eq. 566.47)}$$

However, the solution to this set of equations requires an iterative approach as S is a function of the PV temperature (and hence the fluid temperature), the radiation heat transfer coefficients are functions of the surface temperatures, and the fluid convection coefficient is also temperature dependent. The iterative approach is summarized below:

1. Guess values for the mean fluid temperature, mean PV cell temperature, mean back surface temperature, mean cover temperature, and mean air channel surface temperatures.
2. Calculate the radiation heat transfer coefficients using equations 566.2, 566.18, and 566.20.
3. Calculate the PV cell efficiency and S using equations 566.9 through 566.14.
4. Calculate the fluid heat transfer coefficient using equations 566.27 through 566.33.
5. Calculate the fluid outlet temperature using equation 566.39 and the mean fluid temperature using equation 566.41.
6. Calculate the mean surface temperatures using equations 566.43 through 566.47.
7. Repeat steps 2 to 6 until convergence is reached

The remaining relevant heat transfers for the collector are then calculated as:

$$Q_{loss,top,conv} = h_{conv,top}\ Area \left(\overline{T}_{Cover} - T_{amb}\right) \quad \text{(Eq. 566.48)}$$

$$Q_{loss,top,rad} = h_{rad,top}\ Area \left(\overline{T}_{Cover} - T_{sky}\right) \quad \text{(Eq. 566.49)}$$

$$Q_{loss,back,conv} = h_{conv,back}\ Area \left(\overline{T}_3 - T_{back}\right) \quad \text{(Eq. 566.50)}$$

$$Q_{loss,back,rad} = h_{rad,top}\ Area \left(\overline{T}_3 - T_{back,rad}\right) \quad \text{(Eq. 566.51)}$$

$$Q_{absorbed} = Area\,(\tau\alpha)_n\ IAM\ G_T\ (1-\eta_{PV}) \quad \text{(Eq. 566.52)}$$

$$Power_{PV} = Area\,(\tau\alpha)_n\ IAM\ G_T\ \eta_{PV} \quad \text{(Eq. 566.53)}$$

With these definitions in place, an energy balance around the collector can be written as:

$$Q_{absorbed} + Power_{PV} = Q_u + Q_{loss,top,conv} + Q_{loss,top,rad} + Q_{loss,back,conv} + Q_{loss,back,rad} \quad \text{(Eq. 566.54)}$$

APPENDIX 1:

Sample Data File for the PV Efficiency as a Function of the Cell temperature and Incident Solar Radiation

```
0   5000     !Incident Solar Radiation Values in kJ/h.m2
-50  -40  -30  -20  -10  0  10  20  30  40  50  60  70  80  90  100  110  120  130  140  150  !Cell Temperature (C)
0.100   !Efficiency at Solar=0 and Temperature=-50
0.095   !Efficiency at Solar=0 and Temperature=-40
0.090   !Efficiency at Solar=0 and Temperature=-30
0.085   !Efficiency at Solar=0 and Temperature=-20
0.080   !Efficiency at Solar=0 and Temperature=-10
0.075   !Efficiency at Solar=0 and Temperature=0
0.070   !Efficiency at Solar=0 and Temperature=10
0.065   !Efficiency at Solar=0 and Temperature=20
0.060   !Efficiency at Solar=0 and Temperature=30
0.055   !Efficiency at Solar=0 and Temperature=40
0.050   !Efficiency at Solar=0 and Temperature=50
0.045   !Efficiency at Solar=0 and Temperature=60
0.040   !Efficiency at Solar=0 and Temperature=70
0.035   !Efficiency at Solar=0 and Temperature=80
0.030   !Efficiency at Solar=0 and Temperature=90
0.025   !Efficiency at Solar=0 and Temperature=100
0.020   !Efficiency at Solar=0 and Temperature=110
0.015   !Efficiency at Solar=0 and Temperature=120
0.010   !Efficiency at Solar=0 and Temperature=130
0.005   !Efficiency at Solar=0 and Temperature=140
0.000   !Efficiency at Solar=0 and Temperature=150
0.100   !Efficiency at Solar=5000 and Temperature=-50
0.095   !Efficiency at Solar=5000 and Temperature=-40
0.090   !Efficiency at Solar=5000 and Temperature=-30
0.085   !Efficiency at Solar=5000 and Temperature=-20
0.080   !Efficiency at Solar=5000 and Temperature=-10
0.075   !Efficiency at Solar=5000 and Temperature=0
0.070   !Efficiency at Solar=5000 and Temperature=10
0.065   !Efficiency at Solar=5000 and Temperature=20
0.060   !Efficiency at Solar=5000 and Temperature=30
0.055   !Efficiency at Solar=5000 and Temperature=40
0.050   !Efficiency at Solar=5000 and Temperature=50
0.045   !Efficiency at Solar=5000 and Temperature=60
0.040   !Efficiency at Solar=5000 and Temperature=70
0.035   !Efficiency at Solar=5000 and Temperature=80
0.030   !Efficiency at Solar=5000 and Temperature=90
0.025   !Efficiency at Solar=5000 and Temperature=100
0.020   !Efficiency at Solar=5000 and Temperature=110
0.015   !Efficiency at Solar=5000 and Temperature=120
0.010   !Efficiency at Solar=5000 and Temperature=130
0.005   !Efficiency at Solar=5000 and Temperature=140
0.000   !Efficiency at Solar=5000 and Temperature=150
```