TYPE 561: UN-GLAZED AIR-HEATING COLLECTOR

This component is intended to model an un-glazed solar collector that passes air behind the absorbing plate. Moist air calculations are not included in 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.

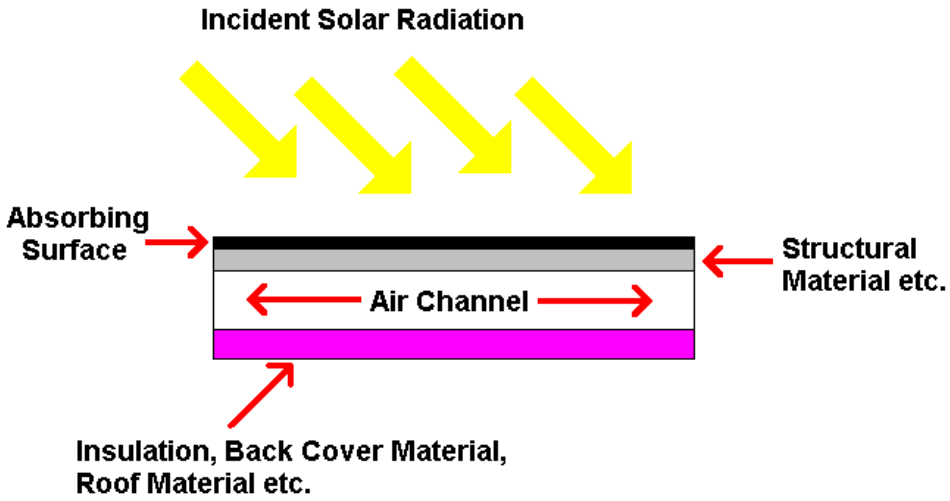


Figure 1 –Collector Schematic

Nomenclature

β	- slope of the collector surface
η	- efficiency
θ	- angle of incidence
ρ	- ground reflectance
$\tau\alpha$	- transmittance-absorptance product for the solar collector
ε_{back}	- emissivity of the back surface of the collector
ε_{plate}	- emissivity of the top surface of the collector
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

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	- incidence angle modifier multiplier
C_p	- specific heat of the fluid flowing through the collector
F_R	- collector heat removal factor
G_t	- total solar radiation (beam + diffuse) incident upon the collector surface
h_{fluid}	- heat transfer coefficient from the fluid in the flow channels to the walls of the flow channel
h_{inner}	- heat transfer coefficient from the back of the collector to the air
h_{outer}	- heat transfer coefficient from the top of the collector (absorbing surface) to the ambient

	air
$h_{rad,bot}$	- the linearized radiation heat transfer coefficient from the back of the collector for long-wave radiation loss calculations
$h_{rad,top}$	- the linearized radiation heat transfer coefficient from the top of the collector (absorbing surface) to the sky
$h_{rad,1-2}$	- the linearized radiation heat transfer coefficient from the top surface of the air channel to the bottom surface of the air channel
IAM	- incidence angle modifier
L	- the length of the collector along the flow direction
$\dot{m}$	- flow rate of fluid through the solar collector
$Q_{loss,top,conv}$	- rate at which energy is lost to the ambient through convection off the top of the collector
$Q_{loss,top,rad}$	- rate at which energy is lost to the sky through radiation off the top of the collector
$Q_{loss,back,conv}$	- 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
$Q_{absorbed}$	-rate at which energy is absorbed by the collector plate
Q_u	- net rate at which energy is added to the flow stream by the collector
R_t	- resistance to heat transfer from the absorbing surface to the upper surface of the flow channel
R_b	- resistance to heat transfer from the lower surface of the flow channel to the back surface of the collector
S	- absorbed solar radiation
$\overline{T}$	- mean temperature
T_{amb}	- ambient temperature for convective losses from the top surface
T_{back}	- environment temperature for convective losses from the bottom surface
$T_{back,rad}$	- temperature for radiative losses from the bottom surface of the collector
T_{fluid}	- bulk 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_{plate}	- absorber plate temperature
U_L	- overall loss coefficient for the collector
W	- the width of the collector
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
h	- total horizontal
n	- normal incidence
nominal	- refers to the reference conditions
s	- sky diffuse
t	- total (beam + diffuse)

Detailed Description:

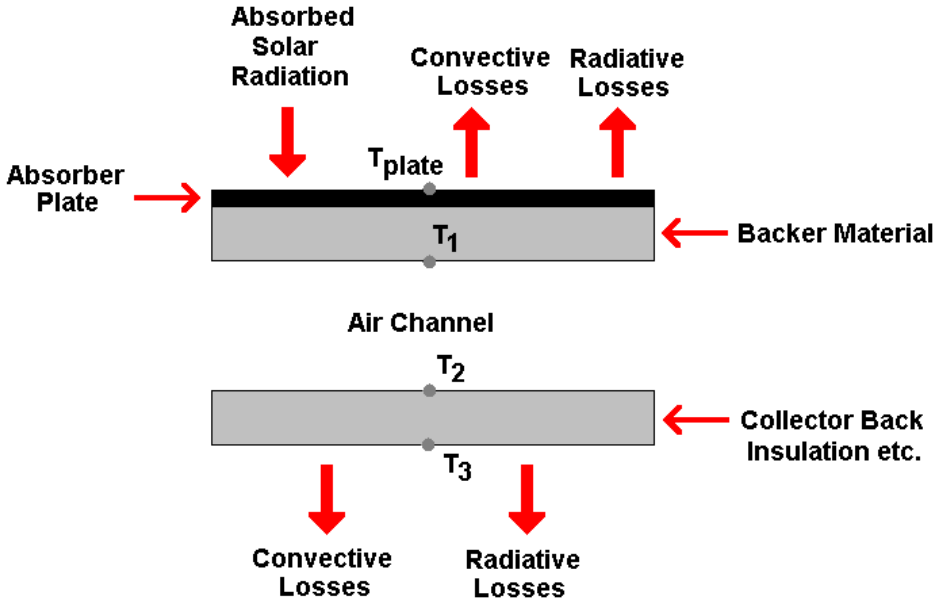


Figure 2 - Collector Definitions

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

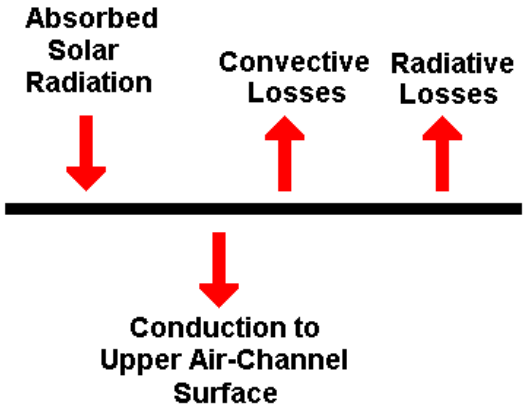


Figure 3: Absorbing Surface Energy Balance

$$0 = S - h_{outer}\left(T_{plate} - T_{amb}\right) - h_{rad,top}\left(T_{plate} - T_{sky}\right) - \frac{\left(T_{plate} - T_1\right)}{R_T} \qquad \text{(Eq. 561.1)}$$

where:

$$h_{rad,top} = \varepsilon_{plate}\,\sigma\left(T_{plate} + T_{sky}\right)\left(T_{plate}^{\,2} + T_{sky}^{\,2}\right) \qquad \text{(Eq. 561.2)}$$

Note: R_T accounts for the conductive resistance of the absorber plate plus the conductive resistance of any other materials located between the absorbing surface and the upper air channel surface.

S is the absorbed solar radiation. 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).

$$IAM = \frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{G_{bT}\ \frac{(\tau\alpha)_b}{(\tau\alpha)_n} \ + \ G_d\ \frac{(1+\cos\beta)}{2}\ \frac{(\tau\alpha)_s}{(\tau\alpha)_n} \ + \ G_h\ \rho_g\ \frac{(1-\cos\beta)}{2}\ \frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{G_T} \qquad \text{(Eq. 561.3)}$$

where:

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) \qquad \text{(Eq. 561.4)}$$

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:

$$\theta_{sky} = 59.68 \ - \ 0.1388\ \beta \ + \ 0.001497\ \beta^2 \qquad \text{(Eq. 561.5)}$$

$$\theta_{ground} = 90.0 \ - \ 0.5788\ \beta \ + \ 0.002693\ \beta^2 \qquad \text{(Eq. 561.6)}$$

With these definitions S, the net absorbed solar radiation from equation 561.1, can be determined as:

$$S = (\tau\alpha)_n\ IAM\ G_T \qquad \text{(Eq. 561.7)}$$

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

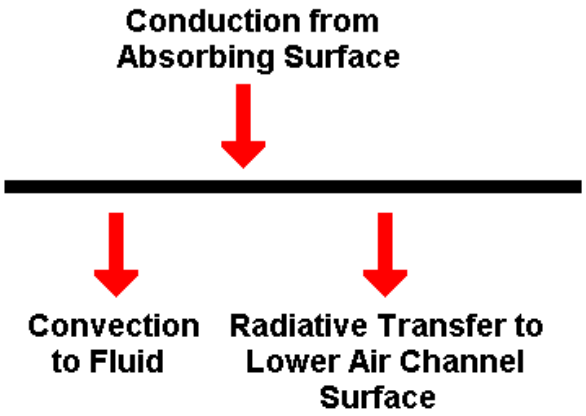


Figure 4: Upper Air Channel Surface Energy Balance

$$0 = \frac{(T_{plate} - T_1)}{R_T} - h_{fluid}(T_1 - T_{fluid}) - h_{rad,1\to 2}(T_1 - T_2) \quad \text{(Eq. 561.8)}$$

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

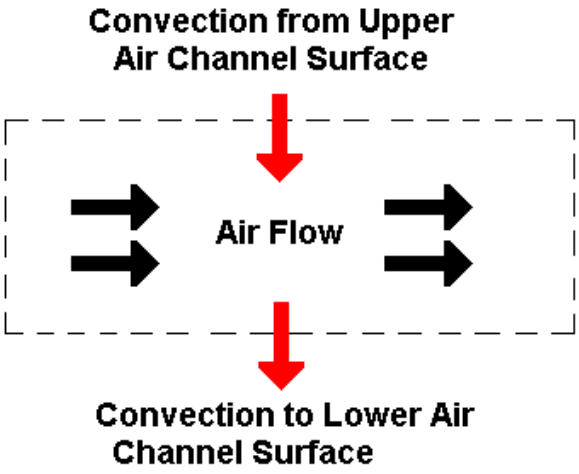


Figure 5: Fluid Energy Balance

$$q''_u = h_{fluid}(T_1 - T_{fluid}) - h_{fluid}(T_{fluid} - T_2) \quad \text{(Eq. 561.9)}$$

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

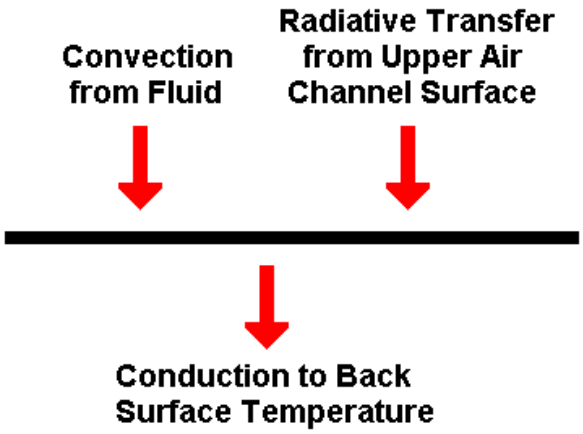


Figure 6: Lower Air Channel Surface Energy Balance

$$0 = h_{fluid}(T_{fluid} - T_2) + h_{rad,1\to 2}(T_1 - T_2) - \frac{(T_2 - T_3)}{R_B} \quad \text{(Eq. 561.10)}$$

where:

$$h_{rad,1\to2} = \frac{\sigma\left(T_1^{\,2} + T_2^{\,2}\right)\left(T_1 + T_2\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \text{(Eq. 561.11)}$$

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

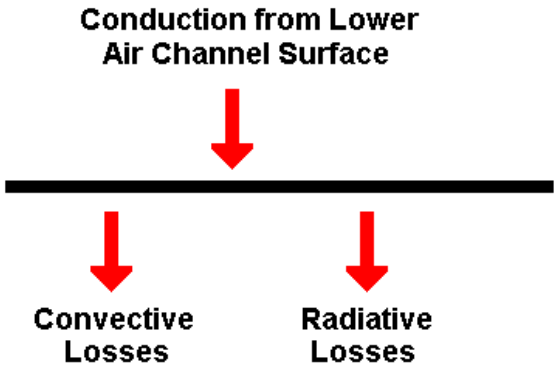


Figure 7: Collector Back Surface Energy Balance

$$0 = \frac{\left(T_2 - T_3\right)}{R_B} - h_{inner}\left(T_3 - T_{back}\right) - h_{rad,bot}\left(T_3 - T_{back,rad}\right) \qquad \text{(Eq. 561.12)}$$

where:

$$h_{rad,bot} = \varepsilon_{back}\,\sigma\left(T_3 + T_{back,rad}\right)\left(T_3^{\,2} + T_{back,rad}^{\,2}\right) \qquad \text{(Eq. 561.13)}$$

Solving Equation 561.1 for T_{plate} and substituting into equation 561.12, we derive the following equation for the collector useful energy gain as a function of the local fluid temperature:

$$\begin{aligned} q_u'' = {} & T_{fluid}\left(\frac{h_{fluid}^{\,2}}{m\ p} + \frac{2\,h_{fluid}^{\,2}\,h_{rad,1\to2}}{m\ p\ x} - 2\,h_{fluid} + \frac{h_{fluid}^{\,2}}{x} + \frac{h_{fluid}^{\,2}\,h_{rad,1\to2}^{\,2}}{m\ p\ x^2}\right) \\ & + \frac{h_{fluid}F'\left(S + h_{outer}T_{amb} + h_{rad,top}T_{sky}\right)}{m\ p} + \frac{h_{fluid}\ \ h_{rad,1\to2}}{m\ p\ x}\left(G'h_{inner}T_{back} + G'h_{rad,bot}T_{back,rad}\right) \\ & + \frac{h_{fluid}\ \ h_{rad,1\to2}}{x}\left(\frac{F'\left(S + h_{outer}T_{amb} + h_{rad,top}T_{sky}\right)}{m\ p} + \frac{h_{rad,1\to2}}{m\ x\ p}\left(G'h_{inner}T_{back} + G'h_{rad,bot}T_{back,rad}\right)\right) \\ & + \frac{h_{fluid}G'\,h_{inner}T_{back}}{x} + \frac{h_{fluid}G'h_{rad,bot}T_{back,rad}}{x} \end{aligned} \qquad \text{(Eq. 561.14)}$$

where:

$$F' = \frac{1}{h_{rad,top}R_T + h_{outer}R_T + 1} \qquad \text{(Eq. 561.15)}$$

$$G' = \frac{1}{h_{rad,bot} R_B + h_{inner} R_B + 1} \quad \text{(Eq. 561.16)}$$

$$x = h_{fluid} + h_{rad,1\to2} + \frac{1}{R_B} - \frac{G'}{R_B} \quad \text{(Eq. 561.17)}$$

$$m = h_{fluid} + h_{rad,1\to2} + \frac{1}{R_T} - \frac{F'}{R_T} \quad \text{(Eq. 561.18)}$$

$$p = 1 - \frac{h_{rad1\to2}^{\ 2}}{m\ x} \quad \text{(Eq. 561.19)}$$

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.

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

$$\dot{m} C_p \frac{dT_{fluid}}{dy} - W q''_u = 0 \quad \text{(Eq. 561.20)}$$

Subbing equation 561.14 into equation 561.20 we find:

$$\frac{dT_{fluid}}{dy} = \left(\frac{W}{\dot{m} C_p}\right) a\, T_{fluid} + \left(\frac{W}{\dot{m} C_p}\right) b \quad \text{(Eq. 561.21)}$$

where:

$$a = \left(\frac{h_{fluid}^{\ 2}}{m\ p} + \frac{2\, h_{fluid}^{\ 2}\, h_{rad,1\to2}}{m\ p\ x} - 2\, h_{fluid} + \frac{h_{fluid}^{\ 2}}{x} + \frac{h_{fluid}^{\ 2}\, h_{rad,1\to2}^{\ 2}}{m\ p\ x^2} \right) \quad \text{(Eq. 561.22)}$$

$$b = \frac{h_{fluid} F' \left(S + h_{outer} T_{amb} + h_{rad,top} T_{sky}\right)}{m\ p} + \frac{h_{fluid}\ h_{rad,1\to2}}{m\ p\ x} \left(G' h_{inner} T_{back} + G' h_{rad,bot} T_{back,rad}\right)$$
$$+ \frac{h_{fluid}\ h_{rad,1\to2}}{x} \left(\frac{F' \left(S + h_{outer} T_{amb} + h_{rad,top} T_{sky}\right)}{m\ p} + \frac{h_{rad,1\to2}}{m\ x\ p} \left(G' h_{inner} T_{back} + G' h_{rad,bot} T_{back,rad}\right) \right)$$
$$+ \frac{h_{fluid} G'\, h_{inner} T_{back}}{x} + \frac{h_{fluid} G' h_{rad,bot} T_{back,rad}}{x} \quad \text{(Eq. 561.23)}$$

If we assume that a and b are independent of position in the collector (y-direction), we can integrate equation 18 from zero to y and find:

$$T_{fluid}(y) = \left(T_{fluid,in} + \frac{b}{a}\right)\exp\left(\frac{W}{\dot{m}\,C_p}\,a\,y\right) - \frac{b}{a} \qquad \text{(Eq. 561.24)}$$

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

$$T_{fluid,out} = \left(T_{fluid,in} + \frac{b}{a}\right)\exp\left(-\frac{Area\ \ a}{\dot{m}\,C_p}\right) - \frac{b}{a} \qquad \text{(Eq. 561.25)}$$

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):

$$\overline{T}_{fluid} = \frac{1}{L}\int_0^L T_{fluid}(y)\,dy \qquad \text{(Eq. 561.26)}$$

Using equation 561.24 and 561.26 and solving the differential equation we find:

$$\overline{T}_{fluid} = \left(\frac{T_{fluid,in} + \frac{b}{a}}{\frac{Area\ \ a}{\dot{m}\,C_p}}\right)\exp\left(\frac{Area\ \ a}{\dot{m}\,C_p}\right) - \left(\frac{T_{fluid,in} + \frac{b}{a}}{\frac{Area\ \ a}{\dot{m}\,C_p}}\right) - \frac{b}{a} \qquad \text{(Eq. 561.27)}$$

Using equation 561.25, and knowing the collector fluid inlet temperature, we can find the collector useful energy gain as:

$$Q_u = \dot{m}\,C_p\left(T_{fluid,out} - T_{fluid,in}\right) \qquad \text{(Eq. 561.28)}$$

Substituting equation 561.1 into 561.8, and then substituting equation 561.12 into 561.10 and equation 561.10 into equation 561.8, we can derive an expression for the upper air channel mean surface temperature as a function of the mean fluid temperature:

$$\overline{T}_1 = \frac{F'}{m\ p}\left(S + h_{outer}T_{amb} + h_{rad,top}T_{sky}\right) + \frac{h_{fluid}\ \overline{T}_{fluid}}{m\ p} + \frac{h_{rad,1\to2}}{m\ p\ x}\left(h_{fluid}\overline{T}_{fluid} + G'h_{inner}T_{back} + G'h_{rad,bot}T_{back,rad}\right) \qquad \text{(Eq. 561.29)}$$

With the upper air channel mean surface temperature known, equation 561.9 can be used to find the lower air channel mean surface temperature:

$$\overline{T}_2 = \frac{Q_u}{h_{fluid}\ Area} + 2\overline{T}_{fluid} - \overline{T}_1 \qquad \text{(Eq. 561.30)}$$

Also with the upper air channel mean surface temperature known, the mean plate temperature can be calculated from equation 561.1.

$$\overline{T}_{plate} = R_T\, F'\left(S + h_{outer} T_{amb} + h_{rad,top} T_{sky} + \frac{\overline{T}_1}{R_T} \right) \quad \text{(Eq. 561.31)}$$

With the lower air channel mean surface temperature known, equation 561.12 can be used to find the mean collector back surface temperature:

$$\overline{T}_3 = R_B\, G'\left(S + h_{inner} T_{back} + h_{rad,bot} T_{back,rad} + \frac{\overline{T}_2}{R_B} \right) \quad \text{(Eq. 561.32)}$$

The solution of this set of equations requires an iterative approach as S is a function of the plate temperature and hence the fluid temperature:

1. Guess values for the mean plate temperature, mean back surface temperature, and mean air channel surface temperatures.
2. Calculate the radiation heat transfer coefficients using equations 561.2, 561.11, and 561.13.
3. Calculate the fluid outlet temperature using equation 561.25 and the mean fluid temperature using equation 561.27.
4. Calculate the mean surface temperatures using equations 561.29 through 561.32.
5. Repeat steps 2 to 4 until convergence is reached

With convergence attained, equation 6.9.3 from Duffie and Beckman can be used to find the overall loss coefficient from the collector (U_L):

$$Q_u = Area \left[S - U_L \left(\overline{T}_{plate} - T_{amb} \right) \right] \quad \text{(Eq. 561.33)}$$

Finally, with the collector overall loss coefficient calculated, the collector heat removal factor can be calculated from equation 6.7.6 of Duffie and Beckman:

$$Q_u = Area\; F_R \left[S - U_L \left(T_{fluid,in} - T_{amb} \right) \right] \quad \text{(Eq. 561.34)}$$

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

$$Q_{loss,top,conv} = h_{outer}\; Area \left(\overline{T}_{plate} - T_{amb} \right) \quad \text{(Eq. 561.35)}$$

$$Q_{loss,top,rad} = h_{rad,top}\; Area \left(\overline{T}_{plate} - T_{sky} \right) \quad \text{(Eq. 561.36)}$$

$$Q_{loss,back,conv} = h_{inner}\; Area \left(\overline{T}_3 - T_{back} \right) \quad \text{(Eq. 561.37)}$$

$$Q_{loss,back,rad} = h_{rad,top}\; Area \left(\overline{T}_3 - T_{back,rad} \right) \quad \text{(Eq. 561.38)}$$

$$Q_{absorbed} = A \left(\tau\alpha \right)_n\; IAM\; G_T \quad \text{(Eq. 561.39)}$$

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

$$Q_{absorbed} = Q_u + Q_{loss,top,conv} + Q_{loss,top,rad} + Q_{loss,back,conv} + Q_{loss,back,rad} \quad \text{(Eq. 561.40)}$$

TRNSYS Component Configuration

PARAMETERS

Parameter Number	Name	Unit	Typical Value	Comment
1	Total collector area	m^2	1.0	The total area of the collector array. This value should be consistent with the PV parameters and the loss coefficients.
2	Fluid specific heat	kJ/kg.K	1.007	The specific heat of the fluid flowing through the solar collector.
3	Reflectance	-	0.1	The overall reflectance of the collector surface at normal incidence. The transmittance-absorptance product at normal incidence is found by subtracting this value from 1.
4	Emissivity – top surface	-	0.9	The emissivity of the collector surface for long-wave radiation exchange with the sky.
5	1^{st} order IAM	-	0.1	1^{st} order coefficient in the IAM function (b_0).
6	Resistance of substrate material	$h.m^2.K/kJ$	0.01	The resistance to heat transfer of the material located between the upper absorber surface cells and the upper flow channel surface. This resistance includes any conductive resistance of the absorber plate as well as any material between the plate and flow channel.
7	Emissivity – top surface of flow channel	-	0.9	The emissivity of the top surface of the flow channel (for radiation across the flow channel).
8	Emissivity – bottom surface of flow channel	-	0.9	The emissivity of the bottom surface of the flow channel (for radiation across the flow channel).
9	Resistance of back material	$h.m^2.K/kJ$	1.0	The resistance to heat transfer for material(s) located between the bottom of the flow channel and the back of the collector.
10	Emissivity – back surface	-	0.9	The emissivity of the collector back surface for long-wave radiation exchange with the environment.

INPUTS

Input Number	Name	Unit	Typical Value	Comment
1	Inlet temperature	C	20.0	The temperature of the fluid entering the collector at the flow inlet.
2	Inlet flow rate	kg/hr	200.0	The flow rate of fluid entering the collector at the fluid inlet.
3	Ambient temperature	C	20.0	The temperature of the environment for calculating losses from the top collector surface.
4	Sky temperature	C	20.0	The temperature of the sky for calculating long-wave radiation losses from the collector surface.
5	Back-surface environment temperature	C	20.0	The temperature of the air located behind the back surface of the collector.
6	Back-surface radiant temperature	C	20.0	The temperature of the surfaces located behind the back surface of the collector for long-wave radiation loss calculations.
7	Incident solar radiation	kJ/hr-m^2	0.0	The rate at which incident solar radiation (beam + diffuse) strikes the sloped collector surface.
8	Total horizontal radiation	kJ/hr-m^2	0.0	The rate at which total solar radiation (beam + diffuse) strikes a horizontal surface.
9	Horizontal diffuse radiation	kJ/hr-m^2	0.0	The rate at which diffuse radiation strikes a horizontal surface.
10	Ground reflectance	-	0.2	The reflectance to solar radiation of the surface upon which the collector is located.
11	Incidence angle	degrees	0.0	The angle of incidence between beam solar radiation and the sloped collector surface.
12	Collector slope	degrees	45.0	The slope of the collector surface of the ICS enclosure (0=horizontal, 90=vertical facing the azimuth).
13	Top loss convection coefficient	kJ/hr-m^2-K	20.0	The convective heat loss coefficient from the top of the collector to the ambient (does not include radiative losses).
14	Back loss convection coefficient	kJ/hr-m^2-K	20.0	The loss coefficient from the back of the collector to the environment (does not include radiative losses).
15	Fluid heat transfer coefficient	kJ/hr-m^2-K	200.0	The heat transfer coefficient from the fluid in the flow channels to the walls of the fluid channel enclosure.

OUTPUTS

Output Number	Name	Unit	Comment
1	Temperature at outlet	C	The temperature of the fluid exiting the collector.
2	Flow rate at outlet	kg/hr	The flow rate of fluid exiting the collector.
3	Useful energy gain	kJ/hr	The net rate at which energy is transferred to the fluid flowing through the solar collector.
4	Thermal efficiency	-	The efficiency of the solar collector in converting incident solar radiation to delivered fluid energy.
5	Collector F_R	-	The calculated collector heat removal factor.
6	Plate temperature	C	The mean surface temperature of the absorber plate.
7	Upper air channel surface temperature	C	The mean temperature of the upper air channel surface.
8	Mean fluid temperature	C	The mean temperature of the fluid in the solar collector.
9	Lower air channel surface temperature	C	The mean temperature of the lower air channel surface.
10	Back surface temperature	C	The mean temperature of the back surface of the collector.
11	Overall IAM	-	The overall (beam plus diffuse) incidence angle modifier for the collector.
12	Collector top losses - convective	kJ/hr	The rate at which energy is lost to the environment through convection from the top surface of the collector.
13	Collector top losses - radiative	kJ/hr	The rate at which energy is lost to the environment through radiation losses from the top surface of the collector.
14	Collector back losses - convective	kJ/hr	The rate at which energy is lost to the environment through convection from the back surface of the collector.
15	Collector top losses - radiative	kJ/hr	The rate at which energy is lost to the environment through radiation losses from the back surface of the collector.
16	Absorbed solar radiation	kJ/hr	The net rate at which solar radiation is absorbed by the collector. This value includes the radiation that was absorbed by the PV cells and converted to electrical energy.
17	Collector U_L	kJ/hr-m^2-K	The calculated overall loss coefficient for this collector.
18	$F_R\tau\alpha_N$	-	The intercept term for the collector efficiency equation.
19	F_RU_L	kJ/hr-m^2-K	The linear term for the collector efficiency equation.