TYPE 544: DOUBLE COVER TOP LOSS MODEL

General Description

Type544 performs a combined radiation and convection energy balance on a plate of known temperature that is separated from an ambient temperature (for convection calculations) and an effective sky temperature (for radiation calculations) by two sheets of cover material. The model iterates to balance energy and to converge upon a temperature for each of the two covers. Wind effects on the outer cover surface are modeled. This model can be used to calculate a time dependent top loss coefficient for solar collector models that take top loss coefficients as an input (as is the case with the TESS Integral Collector Storage (ICS) models). The energy balance methodology of this component was developed at the National Renewable Energy Laboratory [1].

Nomenclature

h_{wind}	[kJ/hr.m2.K]	Convective heat transfer coefficient on the outside of the cover.
k_{air}		Thermal conductivity of air
Re		Reynolds number
Pr		Prandlt Number
$CharLength$	[m]	Collector plate characteristic length
$Length$	[m]	Collector plate length
$Width$	[m]	Collector plate width
$Q_{conv_PlateInnerCover}$	[kJ/hr.m^2]	Convective energy transfer from the plate to the inner cover.
h_{pc}	[kJ/hr.m2.K]	Convective heat transfer coefficient between the plate and inner cover.
T_{Plate}	[ºC]	Plate temperature
T_{Cover}	[ºC]	Cover temperature
$Q_{conv_OuterCoverSky}$	[kJ/hr.m^2]	Convective energy transfer between outer cover and the sky.
$T_{Ambient}$	[ºC]	Ambient temperature
$Q_{rad_Sky2OuterCover}$	[kJ/hr.m^2]	Radiative energy transfer from the sky to the outer cover.
σ		Stefan Botzman constant.
T_{sky}	[ºC]	Effective sky temperature for radiation calculations.
$Q_{rad_InnerCover2Plate}$	[kJ/hr.m^2]	Radiative energy transfer from the cover to the plate.
$\tau_{OuterCover}$	[0..1]	Outer cover transmittance.
$\tau_{InnerCover}$	[0..1]	Inner cover transmittance.
$\rho_{OuterCover}$	[0..1]	Outer cover reflectivity.
$\rho_{OuterCover}$	[0..1]	Inner cover reflectivity.
ε_{Plate}	[0..1]	Plate emissivity
$\varepsilon_{OuterCover}$	[0..1]	Outer cover emissivity
$\varepsilon_{InnerCover}$	[0..1]	Inner cover emissivity
ρ_{Plate}	[0..1]	Plate reflectivity

$Q_{rad_Plate2InnerCover}$	[kJ/hr.m^2]	Radiative energy transfer from the plate to the inner cover.
$Q_{rad_InnerCover2OuterCover}$	[kJ/hr.m^2]	Radiative energy transfer from the inner cover to the outer cover
$Q_{rad_OuterCover2InnerCover}$	[kJ/hr.m^2]	Radiative energy transfer from the outer cover to the inner cover.
$Q_{imbalance}$	[kJ/hr.m^2]	The error in one of two energy balances.
Q_{loss}	[kJ/hr.m^2]	Unmodified amount of energy lost from the cover to the ambient.
U_{top}	[kJ/hr.m^2.K]	Unmodified top loss coefficient for the cover / plate system.
U'_{top}	[kJ/hr.m^2.K]	Top loss coefficient for the cover / plate system as modified by tuning factors
F	[-]	Tuning factor for Q_{loss}

Detailed Description

Type544 takes known values of plate temperature, effective sky temperature, and ambient temperature and calculates cover temperatures that balance convective and radiative energy exchange between the plate, covers and ambient. Figure 1 shows a schematic view of the plate / cover system modeled by Type544.

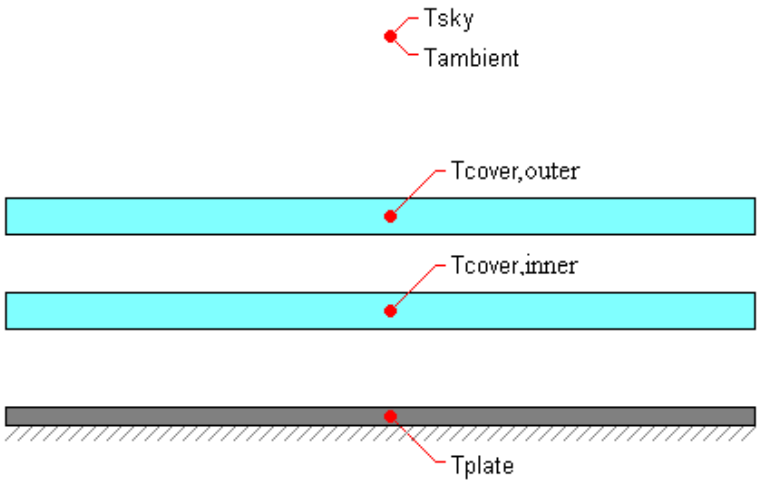


Figure 1: Plate / Cover System Schematic

External Convection

Type544 makes use of three utility subroutines that are provided with the TESS Component Libraries. One of these utilities calculates a forced convective heat transfer coefficient for a flat plate given the wind speed over the plate, the length and width of the plate, the ambient temperature and the ambient atmospheric pressure. These last are used by the external utility to estimate the density and thermal conductivity of the ambient air. The convection coefficient correlation is shown in equation 544.1.

$$h_{wind} = \frac{k_{air}\ 0.86\ \mathrm{Re}^{1/2}\ \mathrm{Pr}^{1/3}}{CharLength} \qquad \text{(Eq. 544.1)}$$

The characteristic length of the rectangular plate is taken as

$$CharLength = \frac{4\ Length * Width}{2(Length + Width)} \quad \text{(Eq. 544.2)}$$

Convection Between Inner Cover and Plate

Type544 makes use of a second utility routine to calculate the convection heat transfer coefficient between the plate and the inner cover. The interior convection coefficient is dependent upon the slope of the plate / cover system, the plate temperature, the inner cover temperature, the plate spacing and the ambient pressure. Because the inner cover temperature is recalculated as the model iterates toward an energy balance, the interior convection coefficient will be recalculated repeatedly during a given time step. For the purposes of the interior convection coefficient calculation, the plate and covers are assumed to be semi infinite, which, given length, width and plate to cover spacings common in solar collectors is a reasonable assumption.

Energy Balance Calculation

The following six equations define the terms of the energy exchange between the plate, the cover and ambient conditions. The convective exchange between the inner cover and the plate is given by:

$$Q_{conv_PlateInnerCover} = h_{pci}\left(T_{Plate} - T_{InnerCover}\right) \quad \text{(Eq. 544.3)}$$

The convective exchange between the two covers is given by

$$Q_{conv_InnerCoverOuterCover} = h_{cico}\left(T_{InnerCover} - T_{OuterCover}\right) \quad \text{(Eq. 544.4)}$$

The convective exchange between the outer cover and the sky is given by:

$$Q_{conv_OIuterCoverSky} = h_{wind}\left(T_{OuterCover} - T_{Ambient}\right) \quad \text{(Eq. 544.5)}$$

The radiative energy transfer from the sky to the cover is:

$$Q_{rad_Sky2Cover} = \sigma\ T_{sky}^{\ 4} \quad \text{(Eq. 544.6)}$$

The radiative energy transfer from the outside cover to the inside cover is:

$$Q_{rad_OuterCover2InnerCover} = \frac{A + B + C}{1 - \dfrac{\rho_{OuterCover}\ \tau_{InnerCover}^{\ 2}\ \rho_{Plate}}{1 - \rho_{Plate}\ \rho_{InnerCover}} - \rho_{InnerCover}\ \rho_{OuterCover}}$$

$$A = \tau_{co}\ \sigma\ T_{sky}^{\ 4} + \rho_{co}\ \varepsilon_{ci}\ \sigma\ T_{InnerCover}^{\ 4} + \varepsilon_{co}\ \sigma\ T_{OuterCover}^{\ 4}$$

$$B = \frac{\rho_{OuterCover}\ \tau_{InnerCover}\ \rho_{Plate}\ \varepsilon_{InnerCover}\ \sigma\ T_{InnerCover}^{\ 4}}{1 - \rho_{Plate}\ \rho_{InnerCover}} \quad \text{(Eq. 543.7)}$$

$$C = \frac{\rho_{OuterCover}\ \tau_{InnerCover}\ \varepsilon_{Plate}\ \sigma\ T_{Plate}^{\ 4}}{1 - \rho_{Plate}\ \rho_{InnerCover}}$$

The radiative energy transfer from the plate to the inside cover is:

$$Q_{rad_Plate2InnerCover} = \frac{A}{1-\rho_{Plate}\ \rho_{InnerCover}} \qquad \text{(Eq. 544.8)}$$

$$A = \rho_{Plate}\ \tau_{InnerCover}\ Q_{rad_InnerCoverOuterCover} + \rho_{Plate}\ \varepsilon_{InnerCover}\ \sigma\ T_{InnerCover}^{\ 4} + \varepsilon_{Plate}\ \sigma\ T_{Plate}^{\ 4}$$

The radiative energy transfer from the inside cover to the plate is

$$Q_{rad_InnerCover2Plate} = \tau_{InnerCover}\ Q_{rad_OuterCover2InnerCover} + \rho_{InnerCover}\ Q_{rad_Plate2InnerCover} + \varepsilon_{InnerCover}\sigma\ T_{InnerCover}^{\ 4} \qquad \text{(Eq. 544.9)}$$

The radiative energy transfer from the inside cover to the outside cover is

$$Q_{rad_InnerCover2OuterCover} = \tau_{InnerCover}\ Q_{rad_Plate2InnerCover} + \rho_{InnerCover}\ Q_{rad_OuterCover2InnerCover} + \varepsilon_{InnerCover}\sigma\ T_{InnerCover}^{\ 4} \qquad \text{(Eq. 544.9)}$$

The radiative energy transfer from the cover back to the sky is:

$$Q_{rad_OuterCover2Sky} = \tau_{OuterCover}\ Q_{rad_InnerCover2OuterCover} + \rho_{OuterCover}\ \sigma\ T_{Sky}^{\ 4} + \varepsilon_{OuterCover}\ \sigma\ T_{OuterCover}^{\ 4} \qquad \text{(Eq. 543.10)}$$

While the above terms could be written as individual energy balances on the cover and on the plate, the above formation can be solved sequentially as is necessary in a linear solving engine such as Fortran provides.

When iteration commences at a given time step, Type544 arbitrarily chooses a cover temperature guess of 0 K. It continues to iterate until it finds an inner cover temperature that causes the following energy imbalance to go to zero.

$$Q_{imbalance} = \left(Q_{rad_Plate2InnerCover} - Q_{rad_InnerCover2OuterCover}\right) + \left(Q_{rad_Plate2InnerCover} + Q_{rad_OuterCover2InnerCover} - Q_{rad_InnerCover2Plate} - Q_{rad_InnerCover2OuterCover}\right) \qquad \text{(Eq. 543.11)}$$

Once the converged inner cover temperature has been found, iteration continues on the outer cover until the following energy balance goes to zero as well

$$Q_{imbalance} = \left(Q_{conv_InnerCoverOuterCover} - Q_{conv_OuterCoverAmbient}\right) + \left(Q_{rad_InnerCover2OuterCover} + Q_{rad_Sky2OuterCover} - Q_{rad_OuterCover2InnerCover} - Q_{rad_OuterCover2Sky}\right) \qquad \text{(Eq. 543.12)}$$

the total losses from the collector / plate system are calculated as

$$Q_{loss} = F\left(Q_{conv_PlateInsideCover} + \left(Q_{rad_Plate2InsideCover} - Q_{rad_InsideCover2Plate}\right)\right) \qquad \text{(Eq. 543.13)}$$

Where F is a tuning factor that can be used when matching simulated and measured results.

The top loss coefficient is calculated as

$$U_{top} = \frac{Q_{loss}}{T_{plate} - T_{ambient}} \qquad \text{(Eq. 543.14)}$$