TYPE 550: TUBULAR INTEGRAL COLLECTOR STORAGE (ICS) SYSTEM

General Description

This component is intended to model an integral collector storage system; a solar collector design where the collector and storage sections of a typical solar domestic hot water system are combined into one unit. The model is intended to be applied to ICS systems that store fluid in several tubes that are connected in series and placed within a collector enclosure.

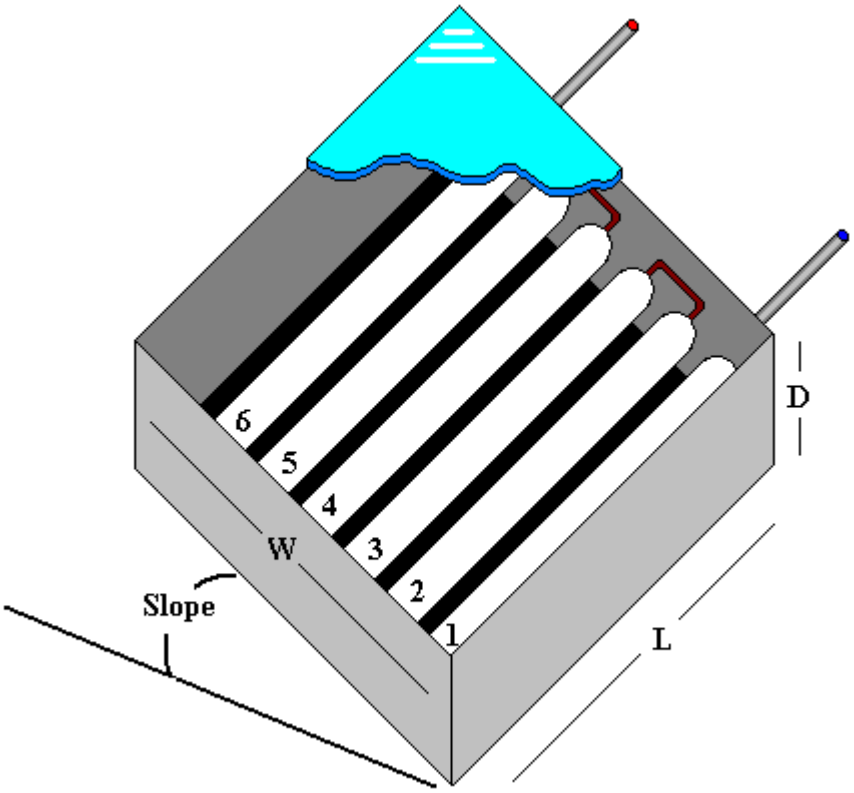


Figure 1 -Typical ICS Schematic

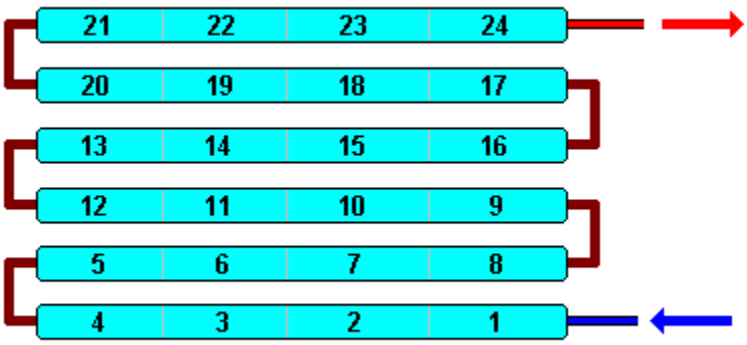


Figure 2 –ICS System with 4 Nodes Per Tube, 6 Tubes

The storage section of the ICS collector is divided into N isothermal temperature nodes; where N is typically chosen to represent the number of tubes in the ICS collector. However, the user has the option of dividing the individual tubes into sections (nodes) as well. The nodes are defined from the inlet of the collector to the outlet of the collector; along the flow direction. The nodes interact thermally with each other through conduction in the water along adjacent nodes in the same pipe (from node 2 to node 3 in Figure 2 for example), conduction in the pipes between adjacent nodes in separate pipes (from node 8 to node 9 in Figure 2 for example), and convection/radiation to corresponding nodes in adjacent tubes (from node 2 to node 7 in Figure 2 for example). The nodes also interact with the environment through solar gains and thermal losses through the cover, edges and bottom surface. This model assumes that the storage enclosure is rectangular as drawn in Figure 1; but other geometries are possible by manipulating the length, width, and depth parameters to achieve the correct top, bottom, and edge areas for loss calculations. The length, width, and depth parameters are used only to calculate the areas; there is no other distinction intended.

Nomenclature

$A_{back,i}$	-	[m^2]	the bottom (back) area of the collector enclosure allocated to this node
$A_{edge,i}$	-	[m^2]	the edge area of the collector enclosure allocated to this node
$A_{solar,i}$	-	[m^2]	the solar cover (top) area allocated to this node for solar gains
$A_{top,i}$	-	[m^2]	the top (cover) area of the collector enclosure allocated to this node
C_{depth}	-	[m]	the depth of the collector enclosure
C_i	-	[kJ/hr.K]	the capacitance of the node
C_{length}	-	[m]	the length of the collector enclosure
C_{width}	-	[m]	the width of the collector enclosure
Cp_i	-	[kJ/kg.K]	the specific heat of the fluid in the node
delt	-	[hr]	the simulation time step
G_t	-	[kJ/hr.m^2]	the total solar radiation (beam + diffuse) incident upon the collector surface (cover)
IAM	-	[0..1]	the incidence angle modifier
m_{in}	-	[kg/hr]	the flow rate of the inlet flow stream
m_{mix}	-	[kg/hr]	the mixing flow rate between unstable adjacent nodes
N	-	[-]	the total number of isothermal temperature nodes for the storage
$Q_{addloss}$	-	[kJ/hr]	the additional losses from the cover of the ICS enclosure per unit area. These losses will be distributed amongst the nodes according to the top loss fraction inputs
$Q_{back,i}$	-	[kJ/hr]	the rate at which energy is lost to the environment from the back of the collector enclosure for the current node
$Q_{cond,i}$	-	[kJ/hr]	the rate of conduction heat transfer into node i from the adjacent nodes
$Q_{del,i}$	-	[kJ/hr]	the rate at which energy is delivered to the flow stream from this node
$Q_{edge,i}$	-	[kJ/hr]	the rate at which energy is lost to the environment from the edges of the collector enclosure for the current node
$Q_{solar,i}$	-	[kJ/hr]	the rate at which incident solar energy is absorbed by the node
$Q_{store,i}$	-	[kJ/hr]	the rate at which energy is stored in the node over the time step
$Q_{top,i}$	-	[kJ/hr]	the rate at which energy is lost to the environment from the top (cover) of the collector enclosure for the current node

$\tau\alpha$	-	[0..1]	the transmittance-absorptance product for the solar collector
T_i	-	[ºC]	the temperature of the current node
T_{i-1}	-	[ºC]	the temperature of the node before the current node
T_{i+1}	-	[ºC]	the temperature of the node after the current node
$T_{final,i}$	-	[ºC]	the temperature of the node at the end of the current time step
$T_{init,i}$	-	[ºC]	the temperature of the node at the beginning of the time step
$T_{inlet,i}$	-	[ºC]	the inlet temperature to this node from the fluid flow stream
T_{loss}	-	[ºC]	the temperature of the environment for losses through the back and edges of the collector enclosure
T_{amb}	-	[ºC]	the temperature of the environment for losses through the top (cover) of the collector
UA_{cond}	-	[kJ/m^2.hr]	the overall heat transfer coefficient for conduction heat transfer between adjacent nodes in adjacent tubes
$UA_{conv,rad}$	-	[kJ/m^2.hr]	the overall heat transfer coefficient for heat transfer between corresponding nodes in adjacent tubes
U_{back}	-	[kJ/m^2.hr]	the heat transfer coefficient for losses from the back of the collector enclosure
U_{edge}	-	[kJ/m^2.hr]	the heat transfer coefficient for losses from the edges of the collector enclosure
U_{top}	-	[kJ/m^2.hr]	the heat transfer coefficient for losses from the top (cover) of the collector enclosure

Detailed Description

1. Capacitance Effects
The model calculates the capacitance of the storage by multiplying the volume of the storage (determined from the tube volume through the length and diameter parameters) by the density of the storage fluid. Additional capacitance (to account for the glass, walls, fins etc.) may be specified by setting the provided parameter greater than zero. This additional capacitance is distributed evenly amongst all the nodes in the storage.

The rate at which energy is stored in the node is calculated by:

$$Q_{store,i} = Ci * (T_{final,i} - T_{init,i}) / delt \qquad \text{(Eq. 550.1)}$$

2. Conduction Between Adjacent Nodes in the Same Tube
The model allows the storage to destratify by allowing heat conduction between adjacent nodes. The heat transfer into node i from adjacent nodes (node i+1 and node i-1) is:

$$Q_{cond,i} = (T_{i+1} - T_i) / R_{cond} + (T_{i-1} - T_i) / R_{cond} \qquad \text{(Eq. 550.2)}$$

Where R_{cond} is calculated from the thermal conductivity of the fluid, the node-to-node spacing, and the conduction area (pipe cross-sectional area).

3. Conduction Between Adjacent Nodes in the Different Tubes
The model allows the storage to destratify by allowing heat conduction between adjacent nodes in different tubes. The heat transfer into node i from adjacent nodes (node i+1 or node i-1) is:

$$Q_{cond,i} = UA_{cond} * (T_{i+1} - T_i) \quad \text{(Eq. 550.3)}$$

Where UA_{cond} is provided by the user.

4. Inlet Flow Effect

The user must specify the inlet temperature and flow rate for a flow stream that passes through the collector. The inlet fluid is assumed to completely mix with the nodal fluid before being passed on to the next node downstream. The corresponding heat transfer due to the flow stream is:

$$Q_{del,i} = m_{in} * Cp_i * (T_i - T_{inlet,i}) \quad \text{(Eq. 550.4)}$$

Where $T_{inlet,i}$ can be the temperature of the node before the current node, or the temperature of the inlet fluid (this node contains the inlet). The model runs with internal iterations if the flow rate would overwhelm the volume of one node in one time step.

5. Losses to the Environment

The model allows the ICS collector to lose energy to the environment through the collector top surface (cover), bottom surface (back), and the edges – plus an additional loss term that is assumed to occur from the cover of the system and can be unevenly divided amongst the nodes (using the fraction of additional losses inputs). The back surface area (collector width times collector length) and the top surface area (same area as back area) are evenly divided amongst the nodes for thermal losses. The collector edge area along the length of the tubes is apportioned to only the nodes in the first and last tubes. The collector edge area along the width of the collector is apportioned only to the first and last nodes in each tube of the collector.

The rate at which energy is lost to the environment for node i is:

$$\begin{aligned} Q_{edge,i} &= U_{edge} * A_{edge,i} * (T_i - T_{loss}) \\ Q_{back,i} &= U_{back} * A_{back,i} * (T_i - T_{loss}) \\ Q_{top,i} &= U_{top} * A_{top,i} * (T_i - T_{amb}) + Q_{addloss} * A_{top,i} * f_{top,loss,i} \end{aligned} \quad \text{(Eq. 550.5)}$$

6. Solar Gains

The amount of solar radiation absorbed into each node can be varied from node to node by specifying the cover area allocated to each node through the use of the "fraction of solar gains" inputs. The solar radiation absorbed into each storage node is then calculated as:

$$Q_{solar,i} = G_t * \tau\alpha * A_{top,i} * f_{top,gain,i} * IAM \quad \text{(Eq. 550.6)}$$

The incidence angle modifier is calculated using 1 of 7 available modes in this model:

Mode 1:

In mode 1, no off-normal effects are considered.

Mode 2: 1st-Order IAM Effects

In this mode, the user must supply the 1st-order coefficient (b_0) of the standard incidence angle modifier function:

$$IAM = 1 - b_0*S \quad \text{(Eq. 550.7)}$$

where $S = 1/\cos(\theta) - 1$, and θ is the incidence angle

Values for this parameter can be found in the SRCC handbook of solar collectors. IAM's for beam, sky diffuse, and ground diffuse are calculated as described above and combined to provide an overall IAM. The effective angles for sky and ground diffuse are calculated using the relations of Brandemuehl (refer to the TRNSYS Type 1 documentation for more information).

Mode 3: 2nd -Order IAM Effects

In this mode, the user must supply the 1st-order coefficient (b_0) and the 2nd-order coefficient (b_1)of the standard incidence angle modifier function:

$$IAM = 1 - b_0*S - b_1*S^2 \quad \text{(Eq. 550.8)}$$

where $S = 1/\cos(\theta) - 1$, and θ is the incidence angle

Values for these parameters can be found in the SRCC handbook of solar collectors. IAM's for beam, sky diffuse, and ground diffuse are calculated as described above and combined to provide an overall IAM. The effective angles for sky and ground diffuse are calculated using the relations of Brandemuehl (refer to the TRNSYS Type 1 documentation for more information).

Mode 4: Single Axis IAM's from a data file

In this mode, the user must supply a data file containing the IAM's as a function of the incidence angle.

$\theta_1\ \theta_2\ \theta_3\ .\ .\ .\ .\ .\ \theta_N$
$IAM_{\theta 1}$
.
.
.
$IAM_{\theta N}$

where:

θ_i = incidence angle at which the IAM is supplied (in increasing order)
$IAM_{\theta i}$ = incidence angle modifier at the given incidence angle

The model calls the DATA subroutine with the given incidence angle and linearly interpolates to find the IAM. IAM's for beam, sky diffuse, and ground diffuse are calculated as described above and combined to provide an overall IAM. The effective angles for sky and ground diffuse are calculated using the relations of Brandemuehl (refer to the TRNSYS Type 1 documentation for more information).

Mode 5: IAM's Based on Cover and Absorber Properties

In this mode, the user must supply several parameters describing the properties of the collector covers and absorber plate. The model then uses the TALF function in TRNSYS to calculate the theoretical IAM's as a function of the incidence angle. IAM's for beam, sky diffuse, and ground diffuse are calculated as described above and combined to provide an overall IAM. The effective angles for sky and ground diffuse are calculated using the relations of Brandemuehl (refer to the TRNSYS Type 1 documentation for more information).

Mode 6: Multiplicative Bi-Axial IAM's

In this mode, the user must supply a file of IAM's as a function of two separate collector angles; the longitudinal angle and the transverse angle. The total IAM will then be the product of these two angular IAM's. This assumption works fairly well for optically non-symmetric collectors such as evacuated tubes and CPC's. A nice description of this approach can be found in the TRNSYS Type 1 documentation. The file format is given below:

$\theta_1\ \theta_2\ \theta_3\ .\ .\ .\ .\ .\ \theta_N$
$IAM_{L1}\quad IAM_{T1}$
.
.
.
$IAM_{LN}\quad IAM_{TN}$

where:

θ_i = angle at which the IAM is supplied (in increasing order)
IAM_{L1} = incidence angle modifier at the specified collector longitudinal angle
IAM_{T1} = incidence angle modifier at the specified collector transverse angle

Mode 7: Bi-Axial IAM's

In this mode, the user must supply a file containing an array of IAM's as a function of two separate collector angles; the longitudinal angle and the transverse angle. The model will calculate the transverse and longitudinal angles based on the incidence angle and the collector slope. The model will then call the DATA subroutine to linearly interpolate between points in two directions to find the IAM at the required combination. Unlike previous modes that assumed the IAM was the product of the IAM at the transverse angle and the IAM at the longitudinal angle, this model allows the user to input the IAM exactly as it should be for the desired combination of angles.

The user must also supply a file of bi-axial incidence angle modifier data in the format:

$T_1\ T_2\ T_3\ .\ .\ .\ .\ .\ T_N$
$L_1\ L_2\ L_3\ .\ .\ .\ .\ .\ L_N$
$IAM_{T1,L1}\ \ IAM_{T1,L2}\ .\ .\ .\ .\ IAM_{T1,LN}$
$IAM_{T2,L1}\ \ IAM_{T2,L2}\ .\ .\ .\ .\ IAM_{T2,LN}$

.
.
.
$IAM_{TN,L1}$ $IAM_{TN,L2}$ . . . . $IAM_{TN,LN}$

where:

T_i = transverse collector angle at which the IAM is supplied (in increasing order)
L_i = longitudinal collector angle at which the IAM is supplied (in increasing order)
$IAM_{Ti,Li}$ = incidence angle modifier at the combination of transverse and longitudinal angles specified

7. Solution Method
The problem breaks down into the required solution of N coupled differential equations:

$$dT_i/dt = (Q_{in,i} - Q_{out,i})/C_i \quad \text{(Eq. 550.9)}$$

where $Q_{in,i}$ and $Q_{out,i}$ account for the solar gains, thermal losses to the environment (top, back, edges), flow rate effects, and heat transfer between nodes.

While there are numerical methods to solve coupled differential equations, we decided to solve the problem with an approximate analytical solution. The analytical solution has several inherent advantages over numerical solutions. First, the subroutine solves its own mathematical problem and does not have to rely on non-standard numerical recipes that must be attached to the subroutine. In this way, the subroutine can be imported into any FORTRAN compiler without having to consider importation of numerical recipe libraries. Secondly, numerical solutions are extremely dependent on the simulation time step and may not converge under certain circumstances commonly encountered in domestic hot water systems (namely high flow rates for example). The analytical solution is time step independent but does require an iterative solution inside the subroutine to solve the coupled differential equations. While solving coupled differential equations iteratively can sometimes lead to convergence problems, this does not seem to be the case with this model.

To solve the differential equations analytically, the equations are placed into the form:

$$dT_i/dt = aT_i+b \quad \text{(Eq. 550.10)}$$

where T is the dependent variable, t is time, a is a constant and b may be a function of time or the dependent variable. If b is a constant, than the solution of this differential equation can be readily solved. If b is not constant, then a reasonable approximation to the analytical solution can be found by assuming that b is constant over the time step and equal to its average value over the time step.

At any time (for **a** not equal to zero):

$$T_{final,i} = (T_{initial,i} + b_{ave}/a) * e^{(a\Delta t)} - b_{ave}/a \quad \text{(Eq. 550.11)}$$

where

$$b_{ave} = b(T_{ave,i}) \quad \text{(Eq. 550.12)}$$

and

$$T_{ave,i} = 1/a\Delta t^{*}(T_{initial,i} + b_{ave}/a) * (e^{(a\Delta t)} - 1) - b_{ave}/a \qquad \text{(Eq. 550.13)}$$

With this assumption, the problem becomes straightforward to solve. Simply write the differential equation in the correct form, determine a and b_{ave} and solve for $T_{final,i}$ and $T_{ave,i}$. Then recalculate b_{ave} and iterate until the temperatures converge.

To check to make sure the model is behaving as expected, an overall energy balance is calculated for the model:

$$\text{Error} = -\Sigma Q_{store,i} - \Sigma Q_{solar,i} + \Sigma Q_{back,i} + \Sigma Q_{top,i} + \Sigma Q_{edge,i} + \Sigma Q_{del,i} \qquad \text{(Eq. 550.14)}$$

$$\text{Energy Balance (\%)} = \text{Error} / [\, |\Sigma Q_{store,I}| + |\Sigma Q_{solar,i}| + |\Sigma Q_{back,i}| + |\Sigma Q_{top,i}| + |\Sigma Q_{edge,i}| + |\Sigma Q_{del,i}| \,] \qquad \text{(Eq. 550.15)}$$

The heat transfer due to conduction/convection/radiation between nodes is not included as this is a net zero heat transfer when the entire collector system is considered.