TYPE 537: FLAT PLATE SOLAR COLLECTOR WITH A VARIABLE SPEED PUMP TO MAINTAIN A DESIRED OUTLET TEMPERATURE

General Description

Type537 models a standard flat plate, quadratic efficiency solar collector based on theoretical equations developed in Solar Engineering of Thermal Processes [1]. The flat plate collector is assumed to incorporate a variable speed pump and a control system that adjusts the flow rate of fluid through the collector to maintain a user desired outlet temperature. The model is equipped with minimum and maximum flow rates for the pump; if the calculated values of these parameters are exceeded, the temperature of fluid exiting the collector will not be equal to the user requested temperature.

Nomenclature

$\dot{Q}u$	[kJ/hr]	The useful energy gain of the LPC collector.
A_c	[m^2]	The collector area.
$F_R(\tau\alpha)_n$	[ ]	The efficiency with which solar radiation is absorbed by the plate and removed by fluid flowing through the collector.
I_t	[kJ/hr.m^2]	The total amount of solar radiation incident on the plane of the collector surface.
I_{beam}	[kJ/hr.m^2]	The amount of beam solar radiation incident on the plane of the collector surface.
I_{dif}	[kJ/hr.m^2]	The amount of diffuse solar radiation incident on the plane of the collector surface.
I_{grnd}	[kJ/hr.m^2]	The amount of ground reflected solar radiation incident on the plane of the collector surface.
θ	[degrees]	The incidence angle of beam radiation on the surface of the collector.
θ_{dif}	[degrees]	The effective incidence angle of diffuse radiation on the surface of the collector.
θ_{grnd}	[degrees]	The effective incidence angle of ground reflected radiation on the surface of the collector.
β	[degrees]	The slope of the collector.
$F_R U_L$	[ ]	The collector loss rate.
ΔT	[ºC]	A temperature difference.
R_{test}	[ ]	
g_{test}	[kg/hr]	The mass flow rate of fluid flowing through the collector under test conditions.
Cp_{fluid}	[kJ/kg.K]	The specific heat of the collector fluid.
$F'U_L$	[ ]	
R_1, R_2, R_3	[ ]	Factors used to correct for non test condition flow rates and more than one collector in series.
N_{series}	[-]	The number of collectors in series.
$\dot{m}_{fluid}$	[kg/hr]	The mass flow rate of fluid flowing through the collector at any given time.
A_c	[m^2]	The area formed by the mouth of the parabolic reflector and the length of a single collector tube.
$F_R U_L{}'$		
$F_R TWO$		
ρ_{grnd}	[0..1]	The reflectance of the ground in front of the collector array

IAM	[0..1]	The overall Incidence Angle Modifier; a dimensionless parameter that accounts for the collector's change in the transmittance absorptance product when the sun is not normal to the plane of the collector.
IAM_{beam}	[0..1]	The beam radiation Incidence Angle Modifier; a dimensionless parameter that accounts for the collector's change in the transmittance absorptance product when beam radiation is not normal to the plane of the collector.
IAM_{dif}	[0..1]	The diffuse radiation Incidence Angle Modifier; a dimensionless parameter that accounts for the collector's change in the transmittance absorptance product when the effective incidence angle of diffuse ratdiation is not normal to the plane of the collector.
IAM_{grnd}	[0..1]	The ground reflected radiation Incidence Angle Modifier; a dimensionless parameter that accounts for the collector's change in the transmittance absorptance product when the effective incidence angle of ground reflected ratdiation is not normal to the plane of the collector.
T_{in}	[ºC]	The temperature of fluid entering the collector array.
T_{amb}	[ºC]	The ambient dry bulb temperature of the collector's surroundings.
T_{out}	[ºC]	The temperature of fluid exiting the collector array.
$T_{desired}$	[ºC]	The desired (user defined) temperature at which fluid should exit the collector array if possible.

Detailed Description

Incidence Angle Modifiers

Type537 contains two possible methods for determining the incidence angle modifiers (IAMs) of the collector. The incidence angle modifier is a dimensionless parameter between 0 and 1 that describes how the collector's transmittance-absorptance ($\tau\alpha$) product varies as a function of solar incidence angle. For beam and diffuse radiation, Type537 calculates an effective incidence angle as proposed by Brandemuhel [2] and as shown in equations 537.1a and 537.1b

$$\theta_{dif} = 59.68 - 0.1388\,\beta + 0.001497\,\beta^2 \qquad \text{(Eq. 537.1a)}$$

$$\theta_{grnd} = 90.0 - 0.5788\,\beta + 0.002693\,\beta^2 \qquad \text{(Eq. 537.1b)}$$

If the user has chosen to use Type537's one dimensional IAM correlation by supplying only a value of b_0 and supplying a value of 0 for b_1, the value of the beam, diffuse and ground reflected incidence angle modifiers are calculated using the tau-alpha function shown in equation 537.2.

$$IAM = 1 - b_0\left[\frac{1}{\max(0.5,\cos(\theta))} - 1\right] - \left[(1 - b_0)\frac{\max(60,\theta) - 60}{30}\right] \qquad \text{(Eq. 537.2)}$$

If, on the other hand, a value of b1 has been specified, then Type537 uses equations 537.3a, 537.3b, and 537.3c to determine the incidence angle modifier for beam, diffuse and ground reflected radiation respectively.

$$IAM_{beam} = 1 - b_0\left[\frac{1}{\cos\theta} - 1\right] - b_1\left[\frac{1}{\cos\theta} - 1\right]^2 \qquad \text{(Eq. 537.3a)}$$

$$IAM_{dif} = 1 - b_0 \left[\frac{1}{\cos \theta_{dif}} - 1 \right] - b_1 \left[\frac{1}{\cos \theta_{dif}} - 1 \right]^2 \quad \text{(Eq. 537.3b)}$$

$$IAM_{grnd} = 1 - b_0 \left[\frac{1}{\cos \theta_{grnd}} - 1 \right] - b_1 \left[\frac{1}{\cos \theta_{grnd}} - 1 \right]^2 \quad \text{(Eq. 537.3c)}$$

The overall incidence angle modification combines the incidence angle modification of beam, diffuse and ground reflected radiation along with sky and ground view factors and the ground reflectance as shown in equation 537.4.

$$IAM = \frac{IAM_{beam}\ I_{beam} + IAM_{dif}\ I_{dif} \left(\frac{1+\cos\beta}{2} \right) + IAM_{grnd}\ I_{grnd}\ \rho_{grnd} \left(\frac{1-\cos\beta}{2} \right)}{I_t} \quad \text{(Eq. 537.4)}$$

Collector Performance

The thermal performance of the Type537 flat plate solar collector is based upon theoretical equations described in Solar Engineering of Thermal Processes [1].

The standard collector performance equation is shown in equation 536.5.

$$\dot{Q}u = A_c \left[F_R (\tau\alpha)_n\ I_t - F_R U_L\ \Delta T \right] \quad \text{(Eq. 536.5)}$$

Numerous temperature differences (ΔT in the equation above) can be used as the basis of the useful energy gain calculation. Some common standards are the collector inlet temperature minus the ambient temperature or the mean collector fluid temperature minus the ambient temperature. Type537 bases its calculation on the collector inlet temperature minus the ambient temperature. Normally the values of $F_R(\tau\alpha)_n$ and $F_R U_L$ as supplied for a particular mass flow rate and for a single collector in a series string. It is therefore necessary to correct these values based on the actual flow rate and on the actual number of collectors being used in the simulation. The correction factors are referred to as R_1, R_2, and R_3.

Using Type537 as a Standard Flow-Through Device

Because a control signal for the variable speed pump is included among the model's inputs, Type537 can be operated as a simple flow through device in which the mass flow rate of fluid is taken as the user supplied inlet flow rate. Under these conditions, if the flow rate through the collector is non zero (and the pumping control signal input is set to 0) then the model first calculates a parameter called $F_R U_L$' as shown in equation 537.6.

$$F_R U_L{}' = F_R U_L + F_R TWO \left(T_{in} - T_{amb} \right) \quad \text{(Eq. 537.6)}$$

This parameter is then used to determine F'U_L

$$F'U_L = \begin{cases} F_R U_L' & if \quad \dfrac{F_R U_L'}{g_{test}\ Cp_{fluid}} \geq 1 \\ g_{test}\ Cp_{fluid}\ \ln\left(1 - \dfrac{F_R U_L'}{g_{test}\ Cp_{fluid}}\right) & if \quad \dfrac{F_R U_L'}{g_{test}\ Cp_{fluid}} < 1 \end{cases} \qquad \text{(Eq. 537.7)}$$

R_1, R_2, and R_3 and next calculated. R_1 includes a term called R_{test}, shown in equation 537.8.

$$R_{test} = g_{test}\ Cp_{fluid}\left(1 - e^{\left(-F'U_L/\left(g_{test}\ Cp_{fluid}\right)\right)}\right) \qquad \text{(Eq. 537.8)}$$

R_1 is given by equation 537.9.

$$R_1 = \frac{N_{series}\ \dot{m}_{fluid}\ Cp_{fluid}}{A_c}\left(\frac{1 - e^{\left((-F'U_L\ A_c)/\left(N_{series}\ \dot{m}_{fluid}\ Cp_{fluid}\right)\right)}}{R_{test}}\right) \qquad \text{(Eq. 537.9)}$$

R_2 is given by equation 537.10.

$$R_2 = \frac{1 - \left(1 - \dfrac{R_1\ A_c\ F_R U_L'}{\dot{m}_{fluid}\ Cp_{fluid}\ N_{series}}\right)^{N_{series}}}{N_{series}\left(\dfrac{R_1\ A_c\ F_R U_L'}{\dot{m}_{fluid}\ Cp_{fluid}\ N_{series}}\right)} \qquad \text{(Eq. 537.10)}$$

R_3 is given by equation 537.11.

$$R_3 = 1 \qquad \text{(Eq. 537.11)}$$

The modified overall useful energy gain from the collector is based upon equation 536.2 as modified by the inclusion of incidence angle modifier effects, R_1, and R_2.

$$\dot{Q}u = R_1\ R_2\ R_3\ A_c\left[F_R(\tau\alpha)_n\ IAM\ I_t - F_R U_L'\left(T_{in} - T_{amb}\right)\right] \qquad \text{(Eq. 537.12)}$$

The temperature of fluid at the collector outlet is given by equation 537.13.

$$T_{out} = T_{in} + \frac{\dot{Q}u}{\dot{m}_{fluid}\ Cp_{fluid}} \qquad \text{(Eq. 537.13)}$$

Under no flow conditions, if the user provided value of F_RTWO is zero, then the fluid outlet temperature is given by equation 537.14.

$$T_{out} = T_{amb} + \frac{F_R(\tau\alpha)_n\ IAM\ I_t}{F_R U_L'} \qquad \text{(Eq. 537.14)}$$

If a second order value is given, the outlet temperature becomes a quadratic of the traditional form $T_{out} = (-B + (B^2 - 4AC)^{0.5}) / 2A$ in which A, B and C are given in equations 537.15a, 537.15b, and 537.15c.

$$A = F_R TWO \quad \text{(Eq. 537.15a)}$$

$$B = F_R U_L - 2\, F_R TWO\, T_{amb} \quad \text{(Eq. 537.15b)}$$

$$C = F_R TWO\, T_{amb}^{\ 2} - FRUL\, T_{amb} - F_R(\tau\alpha)_n\, IAM\, I_t \quad \text{(Eq. 537.15c)}$$

Using Type537 as a Temperature Controlled Device

As soon as the pump control switch input is turned on (set to a value of 1) then Type537 changes to a mode in which the user supplied flow rate input is ignored and in which the model is allowed to calculate a fluid mass flow rate that results in the user requested outlet temperature if possible.

If the temperature of fluid entering the solar collector is already at or above the desired temperature, the flow rate of the collector is set to zero and the outlet temperature is calculated using either equation 537.13 or 537.14 as appropriate to the user supplied value of F_RTWO. If, however, the temperature of fluid entering the collector is below the desired outlet temperature, then Type537 begins an iterative process to back calculate the appropriate value of the mass flow rate. The model first guesses that the flow rate should be set at its maximum possible level. It then proceeds through its calculations of equations 537.9 through 537.12, maintaining that assumption. After calculating the useful energy gain, Type537 calculates a desired mass flow rate as shown in equation 537.16.

$$\dot{m}_{fluid} = \frac{\dot{Q}u}{Cp_{fluid}(T_{desired} - T_{in})} \quad \text{(Eq. 537.16)}$$

It then recalculates the value of R1 using equation 537.9 and the newly calculated mass flow rate. If the value of R1 matches the previously calculated value of R1, then the flow rate is determined to have converged and the model takes the desired temperature as the outlet temperature and exits. If R1 does not match its previously calculated value and less than 100 iterations have occurred Type537 begins its calculation of equations 537.9 through 537.12 again, this time with the newly calculated mass flow rate. Iteration continues until the difference between successive values of R1 reaches 0.01 or until 100 iterations have occurred.

If the calculated flow rate exceeds the maximum allowable flow rate set as a parameter to this model, Type537 will run at the maximum allowable flow rate. If the calculated flow rate is less than the minimum allowable flow rate (also set as a parameter to the model) then the collector pump will automatically shut off and the flow rate will be set to 0.

References

[1] Duffie, J.A., and W.A. Beckman; Solar Engineering of Thermal Processes; J. Wiley and Sons, 1991
[2] Brandemuhel, M.
[3] "Directory of SRCC Certified Solar Collector and Water Heating System Ratings;" Solar Rating and Certification Corporation, 2000