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CONTROL PROBLEMS IN SOLAR DOMESTIC HOT WATER SYSTEMS

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Abstract—The settings on the controller for a solar domestic hot water system can have major impact on the "ratings" obtained from a 1-day test or simulation. The settings become more critical as the effectiveness of any freeze protection heat exchanger decreases. This paper develops equations for optimal controller settings that will maximize the simulated performance. The practice of using solar radiation that is constant over hourly periods in both experimental- and simulation-based rating procedures is shown to cause problems. Recommendations are made for controller settings that yield a "fair" rating comparison.

1. INTRODUCTION

It is well known that controls in a solar system can produce instabilities such that the pump(s) cycle on and off. The typical control system has one sensor mounted on the collector absorber plate near the outlet and another mounted in the bottom of the tank. With no flow through the collector, the collector sensor essentially measures the mean plate temperature. With flow, the collector sensor measures the outlet fluid temperature. For a typical application, the turn-on (upper) dead band (the difference between the plate temperature without flow and the bottom of the tank) must be on the order of 10–20 times the turn-off (lower) dead band (the difference between the collector outlet temperature and the bottom of the tank) or instabilities will occur. When a heat exchanger is placed between the collector and the tank, it is shown that both the turn-on and turn-off dead bands must be increased.

Violating the stability criteria is often not a serious problem for real systems since the solar radiation is generally increasing continuously (in the morning) and the system soon reaches a stable condition. Also, collector heat capacity and pipe fluid volume both help to reduce the frequency of the cycling. However, when simulating a solar system, time does not "march on" until the equations are solved; with unstable conditions the equations do not have a solution if collector thermal capacitances and pipe fluid volumes are neglected. It is necessary to recognize this situation in a simulation and "move on." One popular simulation program, TRNSYS (S. A. Klein *et al.*, 1990) "sticks" the controller and thus finds a solution, albeit an incorrect one.

Even if the controller is set for stable conditions, the settings of the two dead bands can have an effect on the rating of the system. If the pumps turn on too early in the morning or turn off too late in the afternoon, so that the value of the collected energy is less than the cost to operate the pumps, then the settings of the two dead bands are too low and both should be increased. If the pumps turn on too late in the morning or turn off too early in the afternoon, some energy that could have been collected is lost and the two dead bands should be decreased. Criteria are established for determining the dead-band settings that will maximize the system rating.

Another control problem arises when testing or simulating a system for rating purposes where the incident solar radiation remains constant for an hour. The collector may stay off for a whole hour if the turn-on criteria is not met at the beginning of the hour. If the dead bands are not properly set, a portion of the potential operation time can be lost. This condition can have a substantial effect on the ratings that are the usual result of these kinds of simulations and experiments.

2. STABLE CONTROLS

Consider the steady state operation of an idealized solar energy system with a solar collector, freeze protection heat exchanger, storage tank with perfect insulation, pumps and controls as shown in Figure 1. This idealized system has a collector with no thermal mass and has pipes with zero mass, zero volume, and perfect insulation. This idealized system will yield the maximum possible performance and is amenable to analysis.

The Hottel–Whillier equation for the collector and heat exchanger combination as presented by Duffie and Beckman (1991) is:[1]

$$Q_u = A_c F'_R [I_T(\tau\alpha) - U_L(T_i - T_a)] \qquad (1)$$

where most of the terms are in common usage and F'_R is found from the DeWinter–Brinkworth heat exchanger factor (DeWinter, 1975; Brinkworth, 1975):

[1] This analysis assumes that the collector efficiency is linear with $\Delta T/I$. If the collector efficiency curve is not a straight line, the slope of the efficiency curve near an efficiency of zero should be used to determine $F_R U_L$ for use in this paper.

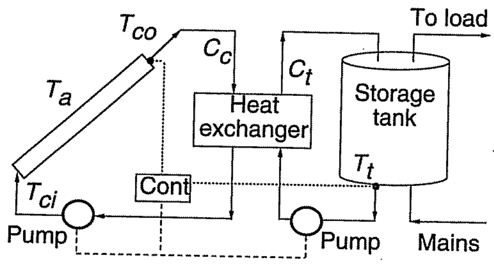

Fig. 1. Typical single tank solar domestic hot water system.

$$\frac{F_R}{F'_R} = 1 + \left(\frac{A_c F_R U_L}{C_c}\right)\left(\frac{C_c}{\epsilon C_{min}} - 1\right) \quad (2)$$

The fluid capacitance rates C_c and C_{min} are the mass flow rate – fluid specific heat products with $C_{min} = min(C_c, C_t)$ where C_c and C_t are the collector and the tank side values, respectively.

If the pumps are turned on by the controller when the temperature difference between the collector and tank equals ΔT_{on}, then the incident radiation on the tilted collector, $I_{T,on}$, is found from

$$I_{T,on}(\tau\alpha) - U_L(T_p - T_a)$$
$$= I_{T,on}(\tau\alpha) - U_L(T_t + \Delta T_{on} - T_a) = 0 \quad (3)$$

where T_t is the temperature at the bottom of the tank and T_p is the plate temperature. The useful energy gain at this turn-on radiation level is found by substituting $I_{T,on}$ from eqn (3) into eqn (1) to yield:

$$Q_{u,on} = A_c F'_R U_L \Delta T_{on} \quad (4)$$

The ϵ-NTU (Beckman and Duffie, 1991) expression for the energy transfer across the heat exchanger, which in steady state operation is the same as the collector useful gain, is:

$$Q_{u,on} = C_c(T_{co} - T_{ci})$$
$$= \epsilon C_{min}(T_{co} - T_t) = \epsilon C_{min} \Delta T_{off} \quad (5)$$

Equating eqns (4) and (5) yields the stability relationship between the turn-on dead band, ΔT_{on}, and the turn-off dead band, ΔT_{off}. Actually, stability is achieved when the following inequality is satisfied.

$$\frac{\Delta T_{on}}{\Delta T_{off}} \geq \frac{\epsilon C_{min}}{A_c F'_R U_L} \quad (6)$$

For a solar system without a heat exchanger, ϵ is equal to 1, C_{min} is equal to C_c, and F'_R is equal to F_R so that eqn (6) reduces to eqn (10.4.6) of Duffie and Beckman (1991).

With the definition of F'_R from eqn (2), eqn (6) can be written as

$$\frac{\Delta T_{on}}{\Delta T_{off}} \geq \frac{\epsilon C_{min}}{C_c}\left(\frac{C_c}{A_c F_R U_L} - 1\right) + 1 \quad (7)$$

Figure 2 is a plot of eqn (7) and shows that at fixed flow rates the maximum stable value of $\Delta T_{on}/\Delta T_{off}$ decreases as the effectiveness decreases. As shown below for optimal conditions, both ΔT_{on} and ΔT_{off} must increase with decreasing effectiveness if stable conditions are to be maintained but ΔT_{off} increases faster than ΔT_{on}.

3. OPTIMAL DEAD BANDS

The pumps of a solar system require electrical energy to operate. Some fraction of this energy, $\mathcal{F}$, is delivered to the working fluid; the remaining fraction, $(1 - \mathcal{F})$, is lost to the surroundings. It is well known that the optimal condition is for the controller to turn on the pumps when the value of the solar energy delivered to the load plus the value of the pump energy that is ultimately delivered to the load just exceeds the value of the energy needed to operate the pumps. Not all of the collector energy and pump energy that heats the water is delivered to the load since tank losses will dissipate some of this energy to the surroundings. However, tank losses are small (in this paper, zero) in a well designed system and to a good approximation these optimal conditions can be expressed as:

$$Q_{u,turn\ on} = (K - \mathcal{F})P_{parasitic}$$
$$= \epsilon C_{min}(T_{co} - T_t) = \epsilon C_{min} \Delta T_{off} \quad (8)$$

where the factor K is the ratio of the cost of parasitic energy (e.g., electricity) to the cost of the auxiliary energy (e.g., gas). In dimensionless form:

$$\frac{\Delta T_{off} C_c}{(K - \mathcal{F})P_{parasitic}} = \frac{C_c}{\epsilon C_{min}} \quad (9)$$

One important result from eqn (9) is that ΔT_{off} should vary inversely with the heat exchanger effectiveness. Once ΔT_{off} is chosen, either arbitrarily or by the criteria of eqn (9), the stable upper dead band, ΔT_{on} can be evaluated from eqn (7). If eqn (9) is used

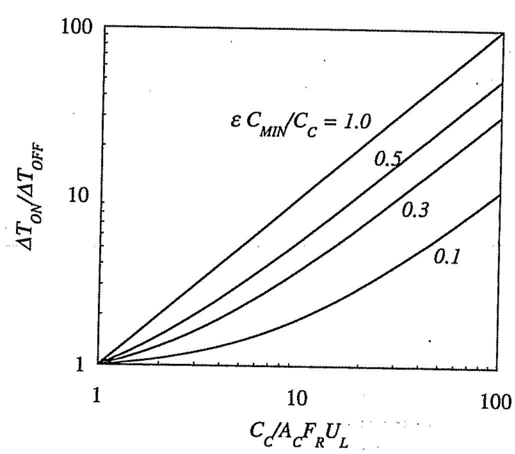

Fig. 2. Dead-band stability criteria as a function of collector flow rate and heat exchanger effectiveness.

Table 1. System parameters for the TRNSYS simulations

$F_R(\tau\alpha)$	0.725
$F_R U_L$	3.20 W/m^2 K
Collector fluid capacitance rate	243 W/K
Collector fluid specific heat	3.77 kJ/kg K
Collector area	6.0 m^2
Collector loop parasitic power	122 W
Tank loop fluid capacitance rate	304 W/K
Tank loop parasitic power	122 W
Collector HX effectiveness	variable
Tank volume	303 liters

for ΔT_{off} then the optimal and stable value for ΔT_{on} is:

$$\frac{\Delta T_{on} C_c}{(K - \mathcal{F}) P_{parasitic}} = \frac{C_c}{\epsilon C_{min}} + \frac{C_c}{A_c F_R U_L} - 1 \qquad (10)$$

As an illustration, a steady-periodic, 1 day TRNSYS simulation was performed with $\mathcal{F}$ set to zero (none of the pump energy goes into the fluid) and K set to unity (parasitic energy and auxiliary energy both electricity). The parameters used in the system simulation are given in Table 1. Figure 3 shows the difference between the collector useful energy gain and the parasitic power as a function of time. The parasitic power has been chosen to be large to illustrate the effects. In this situation both the upper and lower dead bands were too small but the stability criteria was met. At approximately 0615 hours, the collector turns on but the collector energy does not exceed the parasitic power until approximately 0645 hours. A similar situation occurs in the late afternoon. The hot water draws that occur at 0800, 1200, and 1700 hours cause the sudden changes in the net useful energy gain. The late afternoon draw replaces water in the bottom of the tank with mains water and, as a result, the collector turns back on for a short period.

The situation shown in Figure 3 is for dead bands that are too small. With either optimal dead bands or dead bands that are too large, the difference between the useful gain and the parasitic power is always positive. However, the operating time (time from turn-on to turn-off) for the optimal conditions is greater than the operating time for non-optimal conditions.

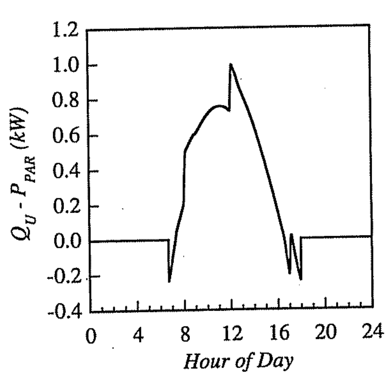

Fig. 3. Collector useful energy gain minus parasitic power as a function of time.

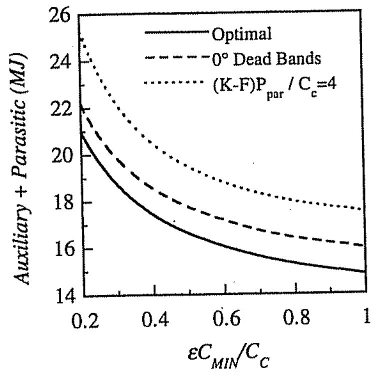

Fig. 4. One-day performance with optimal and non-optimal control settings for the conditions of Table 1.

Figure 4 illustrates the impact of using different criteria for choosing ΔT_{on} and ΔT_{off} as a function of heat exchanger effectiveness. The lower curve is for $(K - \mathcal{F})P_{parasitic}/C_c = 1$ (the optimal condition), the middle curve is for $(K - \mathcal{F})P_{parasitic}/C_c = 0$ (both dead bands too small), and the upper curve is for $(K - \mathcal{F})P_{parasitic}/C_c = 4$ (both dead bands too large).[2] As expected, the optimal condition uses the least auxiliary plus parasitic energy.[3] Similar results are obtained for conditions in which the stability criterion is met but either the upper, the lower or both dead bands are not at their optimal setting.

If ΔT_{on} and ΔT_{off} are fixed at some value, say optimal and stable conditions for a perfect heat exchanger, then in a simulation with decreasing heat exchanger effectiveness the simulated controller will go unstable and simulations can yield erroneous results. The method of "solving" the unstable equations in TRNSYS is to force the controller to make an arbitrary decision (i.e., to "stick") and then solve the resulting equations. In annual simulations this does not cause a significant problem since the decision sometimes over predicts, and sometimes under predicts, performance. For a 1-day simulation this cancellation of errors often does not occur and spurious results are possible. As an example of these spurious results with unstable dead bands, TRNSYS predicts that maximum performance will occur with a heat exchanger effectiveness of less than one.[4] Using stable dead bands in a short-term simulation will always (slightly) over predict the real performance. The alternative is to add thermal capacitance and fluid volume in the collector, heat exchanger, and piping network models and simulate with very small time steps that can follow the instabilities and thus greatly increase the computation time.

[2] For these simulations both the auxiliary and parasitic energy were electricity. Choosing different values of $(K - \mathcal{F})P_{parasitic}/C_c$ in effect chooses stable values of both ΔT_{on} and ΔT_{off}, at an appropriate multiple of the optimal settings.

[3] If the auxiliary energy were gas and the parasitic energy were electric, Fig. 4 would have been plotted as the sum of the auxiliary energy and K times the parasitic energy.

[4] Cliff Murley of the Sacramento Municipal Utility District was first to point out this absurd condition.

The conditions leading to the optimal settings given by eqns (9) and (10) may not be met in practice. The temperature of the collector, heat exchanger, fluid in the pipes, and the pipes may be lower than the bottom tank temperature. In this case it may be beneficial to turn on the pumps at a lower temperature than that given by eqn (10). This effect was neglected in developing the optimal settings resulting in the simulated performance using optimal control settings always being greater than the actual performance.

Unless $(K - \mathcal{F})P_{parasitic}/C_c$ is large, eqn (9) yields small values for ΔT_{off}. In practice, ΔT_{off} is often set to a value somewhat higher than given by Eqn (9) to satisfy practical problems with controllers. If ΔT_{off} is increased to overcome this difficulty, then ΔT_{on} also needs to be increased if stability is to be maintained. This practice causes a penalty in that the pumps are not turned on soon enough in the morning and are turned off too early in the afternoon. In real systems the instability is often not serious. In a simulated system without capacitance in the collector-heat exchanger system the instabilities need to be avoided. Consequently, stable settings should always be used under these conditions.

4. SOLAR RADIATION PROFILE EFFECTS

All of the simulations to this point were done with a smooth radiation profile that was 35% of the June horizontal extraterrestrial horizontal radiation at a latitude of 43°. The conditions for a system test often specify the radiation to be constant over hourly intervals. "Stepped" profiles are used since they are much easier to produce in a solar simulator. Figure 5 shows the steady-periodic daily auxiliary energy plus parasitic energy as a function of $(K - \mathcal{F})P_{parasitic}/C_c$ [choosing $(K - \mathcal{F})P_{parasitic}/C_c$ chooses values for the upper and lower dead bands that are stable and which become the optimal dead bands for the case where $(K - \mathcal{F})P_{parasitic}/C_c = 1$]. The curve is for the case where the solar radiation profile is smooth. The minimum value occurs where $(K - \mathcal{F})P_{parasitic}/C_c$ is approximately 1.[5] The data points in Fig. 5 were obtained for an hourly stepped profile with the same daily total energy. The erratic behavior is an indication of the possible effects of using stepped radiation profiles. For example if the value of $(K - \mathcal{F})P_{parasitic}/C_c$ is changed from 3.5 to 3, a 5% reduction in purchased energy is seen with the smooth profile but no change is seen with the stepped profile. A similar effect would be observed in an actual test.

When simulating a "rating" test, a smooth profile can be used to see if the specified controller dead bands combined with the stepped radiation profile are causing a problem. In a real rating test the manufacturer may be penalized by the choice of dead bands.

[5] The minimum is exactly at $(K - \mathcal{F})P_{parasitic}/C_c = 1$ when simulations are done for a fully mixed storage system. The temperature at the bottom of a stratified storage tank, and consequently the collector useful gain, is affected by the turn-on and turn-off times. For the situation simulated in this paper the effect is that slightly higher than optimal dead bands yield a very slight performance improvement. This highly nonlinear behavior is thought to be small for practical systems and is not included in this analysis.

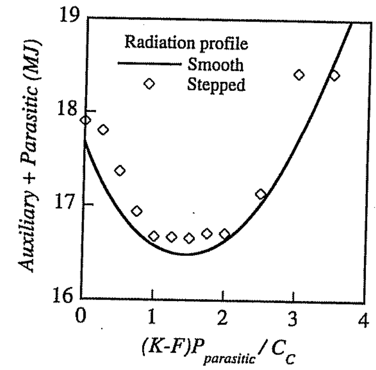

Fig. 5. Auxiliary plus parasitic energy as a function of $(K - \mathcal{F})P_{parasitic}/C_c$ for smooth (curve) and stepped (points) radiation profiles.

5. CONCLUSIONS

The optimal upper and lower dead band settings were derived for a solar energy system with a freeze protection heat exchanger and found to be functions of the heat exchanger effectiveness, fluid capacitance rates, collector parameters, and pumping power. Criteria were established for the dead band settings to ensure stable operation.

By improperly choosing the controller dead band settings, the performance obtained from a real system or from a simulation will be lower than that which is possible. If the dead band settings in a simulation result in unstable operation, unreliable performance estimates may be obtained.

If stable dead band settings are chosen for a particular value of the heat exchanger effectiveness, the simulation may go unstable if the heat exchanger effectiveness is lowered, resulting in unreliable performance estimates. Consequently, only stable controller settings should be used when simulating systems without thermal mass in the collector-heat exchanger subsystem. The use of stable dead bands in a simulation is more important in 1-day rating estimates than in annual performance predictions.

The dead band selection is important in either a simulation or experiment using a stepped radiation profile. Small changes in dead band settings may result in unexpected behavior.

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