SERI/TP-253-2298
UC Category: 59c
DE84004497

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March 1984

To be presented at ASES '84
Anaheim, California
5-9 June 1984

Prepared under Task No. 1598.34
FTP No. 441-84

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A Division of Midwest Research Institute

1617 Cole Boulevard
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Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
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Microfiche A01
Printed Copy A02

SERI/TP-253-2298

EFFECTS OF CONTROL SENSOR DRIFT ON ANNUAL SDHW SYSTEM PERFORMANCE

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ABSTRACT

The determination of proper control set points for active solar energy systems has been discussed by numerous authors. Varying the differential-off set point has been thought to contribute only additional parasitic energy costs. This work shows that the effect of varying the differential-off set point is much more significant than that.

Laboratory testing at the Solar Energy Research Institute has shown that sensor response can drift by as much as 12°C. The sensor testing and results are briefly reviewed. A negative differential-off set point results in an interesting phenomenon. The continued pump circulation keeps the collector sensor warmer than the ambient air and, in fact, will keep it very close to the storage tank temperature. As a result, the pump will continue operating with no irradiation leading to high thermal losses.

Analytical expressions have been developed and are presented that determine the ambient air temperature required to turn the pump off as a function of the (negative) differential-off set point and storage tank temperature. The annual effect of this for five differential-off set points was determined for Albuquerque, Fort Worth, Madison, and Washington, D.C., using TRNSYS. The results show that a negative differential can effectively reduce the net collected energy by 50% and increase the auxiliary energy requirements by 300%.

1. INTRODUCTION

Control systems have been identified as a major reliability problem in active solar energy systems (1-7). The goal of the present study was not to present the frequency of sensor failure but to discuss the implications of sensor failures. The most important include operating the pump when the value of the collected energy is less than the cost to collect it, operating in a mode where the collectors actually reject heat from the storage tank, and loss of overheating and freeze protection. Another goal of this task was to quantify the effect of control sensor degradation on the annual performance of active solar energy systems.

Previous work (8) at the Solar Energy Research Institute (SERI) subjected six control systems to six tests including two sensor tests. The thermistor tests are briefly reviewed here.

2. SENSOR TESTING RESULTS

The thermistors underwent two tests: a characterization test and a stagnation test. First, the resistance response to temperature was measured for each thermistor. Then the thermistors that could be used as collector sensors were attached to a metal plate and heated to 204°C for 224 continuous hours to simulate collector stagnation conditions. Afterwards the resistance at 25°C was compared to the reading before the stagnation test.

The characterization tests for each thermistor were performed using a Guildline Model 9734 constant-temperature bath with a specified temperature stability of ±0.010°C and measured gradients less than 0.002°C in the working volume. Three data points were used to determine the coefficients for the Steinhart-Hart equation[1], and three points were used to check the fit of the curve. Self-heating of the thermistors was also characterized and included in the resistance-temperature curves. The mean residuals were on the order of 0.25°C. The Steinhart-Hart equation can be used to determine the performance of the controller within a mean uncertainty of ±0.25°C for each sensor.

The thermistors were in close agreement at the higher temperatures but showed a signifi-

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[1] $1/T = A + B(\ln R) + C(\ln R)^3$.

cant spread at the lower temperatures. The 3-kΩ and 10-kΩ thermistors had about a 2°C spread near 0°C. Because freeze protection is often controlled by thermistor output, it is important to correct for these temperature response differences. The maximum temperature difference measured by sensors from the same controller manufacturer was 2°C (manufacturer C). This leads to errors in control system operation. The self-heating of the thermistors during the test increased their temperature by approximately 1°C, which was not negligible.

The results of the stagnation test are shown in Table 1. The high-temperature exposure led to outgassing and softening of some of the sealants. The water-resistant seal was weakened on some of the sensors. All five of the 3-k Ω thermistors and one of the 10-kΩ thermistors failed the stagnation test. Two of the 10-kΩ thermistors were slightly affected by the test and the remaining seven 10-kΩ thermistors passed the test without any significant change in performance.

Since the thermistors degrade from exposure to high ambient temperatures, the collector sensor is more susceptible to degradation than the storage tank sensor. A recent report by ESG (7) shows that there is a higher rate of sensor failures in the summer than the rest of the year, presumably from summertime stagnation conditions. Thus it can not be concluded that the sensors drift together, cancelling any effects of degrading.

3. ANALYSIS

An effective solar energy system requires that the pump operate when solar energy can be collected cost-effectively. Of course, the pump may also serve other functions, such as freeze protection and over-temperature protection. These last two items will not be discussed in detail in this report since a failure in either of those modes will be catastrophic or lead to long-term degradation of the integrity of the system. The selection of the control set points to turn on the pump (ΔT_{ON}) is not critical as long as the set point is within reasonable limits. A good discussion on sensor location and set point selection is given in Reference (9). A further discussion on set point selection and the increased cost of excess operating time is presented in Reference (10).

Table 1. Thermistor Post-Stagnation Results (7)

Thermistor[a]	Sensor Temperature (°C)	Calculated Temperature[b] (°C)	Difference [°C (°F)]
3000-Ω Sensors			
B1	26.0[c]	29.65	-3.65 (- 6.57)
B2	2.60[c]	34.18	-8.18 (-14.72)
E1	26.00	23.54	2.46 (4.43)
E2	-[d]	-[d]	-[d]
E3	26.00	13.21	12.79 (23.02)
10,000-Ω Sensors			
A1	26.05	25.84	0.21 (0.38)
A2	26.05	25.96	0.09 (0.16)
C1-1	26.11	25.09	1.09 (1.96)
C1-2	26.06	25.88	0.18 (0.32)
C2-1	26.09	25.88	0.21 (0.38)
C2-2	26.06	25.91	0.15 (0.27)
D1	26.06	26.05	0.01 (0.02)
D2	26.05	25.96	0.09 (0.16)
F1	26.07	25.96	0.11 (0.20)
F2	26.07	25.82	0.25 (0.45)

[a] Letters refer to controller manufacturer and numerals to thermistor number.

[b] Calculated from measured resistance and Steinhart-Hart equation.

[c] Approximation; sensor resistance unsteady.

[d] Sensor failed; resistance increased steadily with time.

An important aspect of selecting a proper differential set point has not been mentioned yet. This is the problem of increased thermal losses from the system when the actual differential-off temperature becomes negative. That is, when the pump will only stop when the collector outlet temperature is less than the storage tank temperature. It might be thought that even if the differential-off temperature is negative that the pump will turn off soon after the sun sets because of the drop in the ambient temperature. However, this is not the case. Even after the irradiance has ceased, the pump continues to operate, keeping the collector and the sensor warm by a relatively large heat source, the storage tank. Since the system is specifically designed to minimize heat loss, the pump can continue to operate for a substantial amount of time. The pump will cease to operate only when there is sufficient heat loss between the storage tank sensor and collector outlet sensor to cause a sufficient drop in temperature of the circulating fluid. The greatest portion of this heat loss is from the collector to the ambient air. The ambient air temperature is thus the controlling factor for pump shutdown.

The ambient air temperature required to turn off the pump as a function of the system parameters and storage tank temperature can be calculated from an energy balance on the collector as[2]:

$$T_s - T_a = (-\dot{m}C_p/A_cF_RU_L)(\Delta T_{OFF})$$

where

T_s = storage tank temperature
T_a = ambient air temperature
$\dot{m}$ = collector mass flowrate
C_p = collector fluid specific heat
A_c = collector area
F_RU_L = collector heat loss factor
ΔT_{OFF} = negative turn-off differential

The results of this equation are presented in Figure 1.

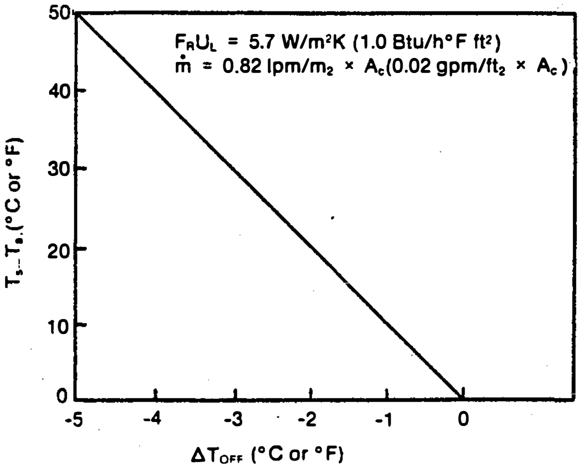

Fig. 1. Ambient temperature depression below storage tank temperature required to stop pump for negative turn-off differential.

If the ambient temperature drops quickly, then the collector sensor will cool quickly due to the high thermal losses from the collector, and the pump will turn off. If the ambient temperature drops slowly, then the storage tank will keep the sensor warm while the storage tank temperature also drops. In this case, the pump can stay on for extended periods of time.

In order to determine the effect on the annual performance of a solar domestic hot water system, computer simulations were performed for four locations: Albuquerque, Fort Worth, Madison, and Washington, D.C. The simulations were performed with TRNSYS 10.0, a component-based, finite difference, transient, heat transfer, simulation model. Although a direct system was simulated, the results may also apply to indirect systems depending on the system configuration, control strategy, etc. The incident solar radiation and the ambient temperatures were derived from hourly TMY data for each of the respective cities. Linear interpolation was used between the hourly TMY data points to provide data for the nine-min. time steps of the simulation. The demand for hot water in each step was interpolated from hourly data in the operating daily pattern estimated by Rand Corp. together with a total daily demand for 60 gal of hot water.

To simulate the effect of sensor degradation, annual sensitivity runs were made in which both the ΔT_{ON} and the ΔT_{OFF} were varied over the ranges of interest. Thus the results are based on a full year of system operation at the degraded ΔTs (i.e., the degradation was assumed to be instantaneous). The system modeled is presented in the Appendix.

4. RESULTS

The results of the computer simulations reveal the degree of the problem stemming from control sensor degradation. Note from Figure 2 that the net annual collected energy is not nearly as dependent on the differential-off temperature when it is positive as when it is negative. The collected energy is not very sensitive to the differential-off temperature when it is positive because when solar radiation is still available for collection after the pump has shut off, the collector temperature will

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[2] See Reference (10) for derivation.

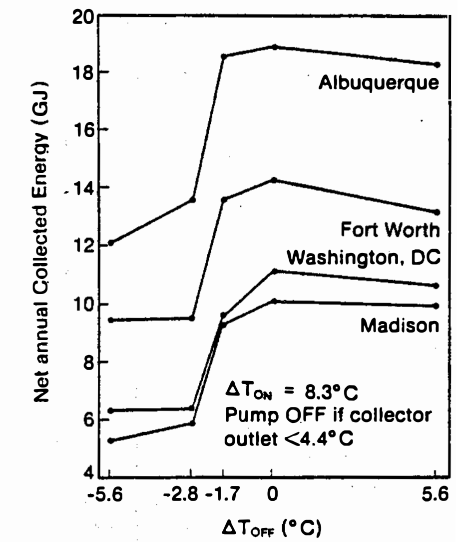

Fig. 2. Net annual collected energy as a function of ΔT_{OFF}.

increase under stagnation conditions until the pump turns on again. One reason to minimize the differential-off temperature is to avoid unnecessary pump cycling, which may lead to premature pump failure or increased maintenance requirements. Since the selection of the differential-off set point is straightforward, it should be set to avoid pump cycling and to prevent operation of the pump when the value of the collected energy is less than the cost of collecting it. As we have seen, another incentive to specify the differential-off set point above zero is to impede it from drifting to below zero from sensor degradation.

The effect of the differential-off temperature becoming negative is easily seen in Figure 2. A negative differential-off set point of only 1.7°C can reduce the net collected energy by as much as 14% (Washington, D.C.). Differential-off temperatures below that amount can reduce the net collected energy by as much as 50% of the collected energy at a differential-off temperature of 0°C. The results for Fort Worth and Washington, D.C. show very little change between -2.8°C and -5.6°C. The computer results showed that the pumps for these systems operated nearly the entire year. Sensor degradation that results in a differential-off temperature of only -2.8°C can cause the pump to operate almost continuously. The pumps did not operate continuously in the TRNSYS simulation because of freeze protection specified in the simulation to prevent the storage tank from dropping below 0°C. Whenever the collector outlet reached 4.4°C, the pump was shut off. In an actual system freezing of pipes or heat exchangers may occur that will stop circulation but also result in extensive damage to the system.

Figure 3 complements the previous figure by presenting the auxiliary energy for each system. The auxiliary energy in TRNSYS is the amount of energy supplied by the auxiliary system that is actually delivered to the end load and as such does not include storage tank losses or inefficiencies of the auxiliary system.

A negative differential-off temperature of 1.7°C can cause a 23% increase in the annual auxiliary energy used (Washington, D.C., Fort Worth) over the 0°C case while a -5.6°C differential-off set point can result in almost a 250% increase (Albuquerque).

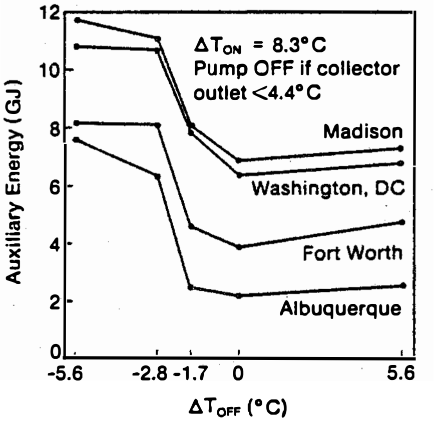

Fig. 3. Annual auxiliary energy as a function of ΔT_{OFF}.

5. CONCLUSIONS AND RECOMMENDATIONS

This study has shown that sensor degradation can result in control instabilities that lead to excess pump operation and loss of collected energy by nighttime operation. This loss of collected energy can be as much as 50% while the auxiliary energy requirements can increase by as much as 250%. Control sensor degradation can be a serious problem. Previous reports have identified control systems as a major problem without specifying the actual consequences. This may be one of the major reliability problems as well as a prime reason why systems are delivering less energy than expected.

Manufacturers and installers should check the calibration of sensors that are in the field, especially those that have undergone repeated or prolonged stagnation conditions. An easier and probably less expensive solution is for controller manufacturers to select thermistors capable of withstanding collector stagnation temperatures and thoroughly test them to determine degradation effects from high temperatures.

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7. APPENDIX

This appendix contains the data for the DHW system simulated.

Collector	
Aperture Area	6.13 m^2
F_R	0.72
$F_R U_L$	6.2 W/°C m^2
K	1.012-0.80 ((1/cos θ)-1)
Slope	Latitude
Azimuth	0.0 Degrees (South)
Ground Reflectance	0.20
Freezing Shutoff Point	4.4°C
Storage	
Solar Tank Volume	454 l
Solar Tank Height to Diameter Ratio	2.5
Solar Tank Insulation	3.5 °C m^2/W
Auxiliary Tank Volume	151 l
Auxiliary Tank Insulation	2.1 °C m^2/W
Auxiliary Tank Efficiency	1.00 (Electric)
Auxiliary Tank Set point	60°C
Ambient Temperature	18°C
Load Profile	RAND
Hot Water Usage	227 l/day
Cold Water Supply Temperature	12.8°C
Transport	
Pipe Length to Collectors	9.1 m
Pipe Length from Collectors	9.1 m
Pipe Insulation	1.1 °C m^2/W
Flow Rate	7.6 l/m
Pump Size	125 W