Title

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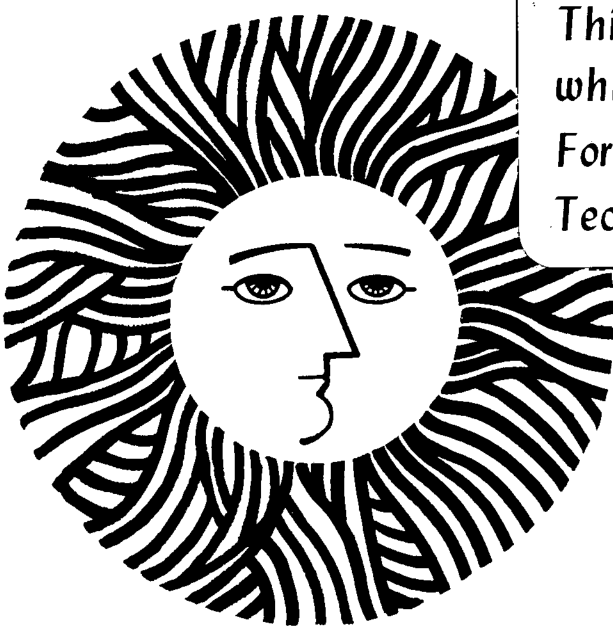

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DISCLAIMER

COMPARISON OF PROPORTIONAL AND ON/OFF SOLAR COLLECTOR LOOP CONTROL STRATEGIES USING A DYNAMIC COLLECTOR MODEL

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ABSTRACT

Common control strategies used to regulate the flow of liquid through flat-plate solar collectors are discussed and evaluated using a dynamic collector model. Performance of all strategies is compared using different set points, flow rates, insolation levels and patterns, and ambient temperature conditions.

The unique characteristic of the dynamic collector model is that it

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includes the effect of collector capacitance. Short term temperature response and the energy-storage capability of collector capacitance are shown to play significant roles in comparing on/off and proportional controllers. Inclusion of these effects has produced considerably more realistic simulations than any generated by steady-state models.

Simulations indicate relative advantages and disadvantages of both types of controllers, conditions under which each performs better, and the importance of pump cycling and controller set points on total energy collection.

NOMENCLATURE

C_a	Effective collector capacitance per unit area
c_p	Thermal capacitance of circulating fluid
F'	Plate fin efficiency factor
K	Proportionality constant for proportional controllers
K_{flow}	Represents the fluid flow rate per unit area
K_{gain}	Represents the collector's gain from insolation and losses to the environment per unit area
$\dot{m}$	Fluid mass flow rate
S	Rate of insolation absorbed by collector plate per unit area
t	Time
T_a	Ambient temperature
$T_{f,x}$	Fluid temperature at position x
T_{in}	Inlet fluid temperature
T_{out}	Outlet fluid temperature
U_L	Collector loss coefficient, per unit area

W_c	Width of collector perpendicular to flow
x	Displacement in flow direction
γ	Pump control indicator
ΔT_{max}	Temperature rise across collector at which flow rate saturates to its maximum, for proportional control
ΔT_{off}	Temperature rise across the collector sufficient to turn off the pump
ΔT_{on}	Temperature rise across the collector sufficient to turn on the pump

INTRODUCTION

Active solar heating systems are generally capital intensive; therefore, improvements which increase system efficiency must do so with only a small incremental initial cost in order for them to help solar energy compete with other energy sources. Since improved control strategies and controllers may satisfy this criterion, researchers and manufacturers have sought to evaluate and improve solar energy system controllers.

Commercially available controllers for domestic heating systems include both on/off and proportional control of the collector flow. On/off controllers have had the widest application due to their simplicity and generally more reliable operation. However, demonstration projects [2,3,6,15,16] have shown that two problems can occur with these controllers; 1) they can cause the circulating pump to cycle on and off excessively and 2) improper selection of set points or installation techniques can cause low system efficiency. In response to some of these problems several controller manufacturers have marketed proportional flow controllers claiming improved overall system efficiencies. This project was undertaken to determine the relative merits of proportional and on/off control so that solar system manufacturers and designers will be able to improve system efficiencies.

DYNAMIC FLAT-PLATE SOLAR COLLECTOR MODEL

The Hottel-Whillier-Bliss collector model [7], as adapted by Klein [10] to include the effects of capacitance, is used to describe the operation of a flat-plate solar collector. The model is based upon a heat balance on a tube and fluid element within a collector, where the entire capacitance of the collector is lumped within the tubes and the circulating fluid. The heat balance is solved using numerical methods on a digital computer to describe the circulating fluid's temperature as a function of time and space.

The transient heat balance equation for a collector element of width W_c is:

$$\begin{aligned} \partial T_{f,x}/\partial t = \gamma \Big[& (F'/C_A)[S - U_L(T_{f,x} - T_a)] \\ & - (\dot{m}c_p/C_A W_C)(\partial T_{f,x}/\partial x)\Big] \\ & + (1-\gamma)\Big[(F'/C_A)[S - U_L(T_{f,x} - T_a]\Big] \end{aligned} \qquad (1)$$

$\gamma = 0$ pump is off

$\gamma = 1$ pump is on

C_A is the weighted average of the total collector capacitance. This equation is for a non-drain down collector. For a drain down system the collector and fluid capacitance would have to be treated separately.

The spatial derivative is eliminated by breaking the collector into a number of stirred tanks; thus, the time dependent temperature of the Nth node is written:

$$dT_N/dt = \gamma\left[(F'/C_A)[S - U_L(T_{f_N} - T_a)] + (\dot{m}c_p/C_A W_c \Delta x)(T_{f_{N-1}} - T_{f_N})\right] + (1 - \gamma)\left[(F'/C_A)[S - U_L(T_{f_N} - T_a)]\right] \quad (2)$$

Fluid temperature at different positions in the collector during discrete time intervals is calculated using the Parasol program [1] which solves differential equations through the use of the fourth-order Runge-Kutta method.

The model described by equation 2 is adopted because; it provides a simple and accurate description of the transient temperature distribution in a collector's circulating fluid, it includes the effects of collector capacitance, it is derived from a well established and respected collector model, and results it provides are usable and consistent with known collector operation.

COLLECTOR PARAMETERS

To compare the various control strategies using a computer model, appropriate parameters must be used which represent a typical flat-plate collector under the influence of common external conditions. Parameter variations are kept to a minimum so that results are easy to interpret and clearly indicate the effects of important variables.

Although a multi-node model is used for the simulations, a single node model of the collector for flow conditions is used to demonstrate the functional dependence of the collector temperature on 1) insolation and ambient temperature, 2) fluid flow rate and 3) collector characteristics:

$$C_A dT_{out}/dt = (K_{gain})f(t) + (K_{flow})T_{in} - (K'_{flow})T_{out}$$

K_{gain} represents the collector's gain from insolation and losses to the environment,

$$K_{gain} = F'[S_{max} + U_L T_{a,max}]$$

f(t) represents the time variation of the normalized forcing function due to insolation and ambient temperature.

K_{flow} represents the fluid flow rate per unit area,

$$K_{flow} = \dot{m}c_p/A_c$$

K_{flow} approximately equals K'_{flow} since $F'U_L << \dot{m}c_p/A_c$.

$$K_{flow} = \dot{m}c_p/A_c + F'U_L$$

By allowing K_{gain} and K_{flow} (and K'_{flow}) to take on either HIGH or LOW values while keeping all other parameters constant, the control strategy comparisons are based on a limited but comprehensive set of collector, meteorological, and flow variations which are used to define limits of operation for a typical collector.

The dynamics associated with the storage tank and the piping are not considered to be critical for comparative results; therefore, the collector inlet temperature, T_{in}, is constant.

Preliminary simulation runs showed that changes in collector capacitance, within the range of suggested capacitances, has a minimal effect on comparisons of different control strategies; therefore, collector capacitance, C_A, is kept constant at 0.7 BTU/ft^2-°F (14.3 kJ/m^2-

°C). This value was suggested by Klein[10] for a two-cover collector and is consistent with values used in other studies[4,12].

The solar day for all runs is 12 hours long with a peak insolation rate reached at hour 6. For modeling of a clear day (no interruptions of insolation) the insolation rate, I, is proportional to a sine wave with a 24 hour period. For a cloudy day (the view of the collector intermittently interrupted) the following equation, that was used by Close[4], determines the insolation rate as a function of time, t, in hours:

$$I = (I_{max}/2)[\sin \pi t/12)][\cos(40\,\pi t/12) + 1]$$

The ambient temperature, T_a, is proportional to a sine wave with a 24 hour period. The peak value is at the 9th hour of the solar day. At sunrise the collector temperature is assumed to equal the ambient temperature.

COLLECTOR FLOW CONTROLLERS

The collection of solar energy is controlled by the flow of fluid through the collector loop, see Fig. 1. Collector outlet and storage tank temperatures are compared by a controller to determine the fluid flow rate. The difference between the collector outlet temperature and the storage tank temperature is known as Δ_T and represents the temperature rise across the collector.

On/Off Flow Control

The on/off controller is a thermostat which turns the fluid circulation pump either on or off based on Δ_T and its previous state. ΔT_{on} is the minimum temperature difference required to turn on the collector loop pump. The pump stays on until the temperature difference falls below ΔT_{off}. The region between ΔT_{on} and ΔT_{off} is known as the hysteresis zone. Because of hysteresis on/off controllers have "memory" which limits pump cycling.

Proportional Flow Control (with saturation)

In this type of feedback controller the fluid flow rate is varied as a function of the temperature rise across the collector, Δ_T. The advantages of a proportionally controlled system are that fluid circulates at lower values of Δ_T and pump cycling is minimized. The fluid flow rate through the collector can be described with the following equations:

$$\dot{m}(t) = \begin{cases} 0 & \text{for } \Delta T < \Delta T_{off} \\ K\Delta T & \text{for } \Delta T_{off} \leq \Delta T \leq \Delta T_{max} \\ \dot{m}_c & \text{for } \Delta T \geq \Delta T_{max} \end{cases}$$

Where: $\dot{m}_c$ = maximum flow rate

DETERMINATION OF CONTROLLER SET POINTS

In determining proper controller set points there are two major considerations: set points must be chosen to maximize energy collection and minimize pumping power(or cost); and set points must be within the capability of the sensors used. The importance of sensor accuracy (and location) cannot be overstressed since it has caused numerous problems in solar installations.

The minimum temperature rise across the collector required for maintaining flow, ΔT_{off}, should be set as low as possible to maximize collection time. However, the set point must be high enough so that; the value of the energy collected always exceeds the cost of parasitic pumping power, the energy collected is greater than that lost in the piping, and the point selected is within the error tolerances of the sensor used.

If the limiting requirement is parasitic power, the maximum ΔT_{off} for on/off or proportional controllers can be determined from the following relationship:

$$\text{(cost of auxiliary power displaced by solar)}(\dot{m}c_p)(\Delta T_{off})$$
$$\geq \text{(required pumping power)(pumping power cost)}$$

For a typical collector system with a flow rate of 10 gpm, a one-quarter horsepower pump motor, and a pumping power to auxiliary power cost ratio of three, ΔT_{off} is only .38°F (.21°C). This small number indicates the general result that parasitic pumping power does not have a critical effect on ΔT_{off} unless a large pump motor is required.

Steady-state temperature drops for typical pipe runs between the storage tank and collectors are shown in Fig. 2 for different pipe inlet-ambient temperature differences. For typical systems the temperature drop in outdoor piping is only about 1°C even for the extreme inlet - ambient temperature difference of 100°C. Therefore for most systems, with moderate size pumps and properly insulated pipes, the limiting requirement for ΔT_{off} is usually temperature sensor accuracy. If higher than necessary values of ΔT_{off} are used, less energy will be collected since the pump will turn on later, shut off sooner, and cycle more than necessary.

Unlike ΔT_{off}, only a range of values can be determined for the upper set points, ΔT_{on} and ΔT_{max}, without knowledge of specific weather conditions.

CONTROLLER AND SET POINT COMPARISONS:

As indicated in Table I six controllers are compared under 8 different sets of conditions. Included in these are two controllers with a 'perfect' timer that allows the pump to come on when the ΔT_{on} criterion is met and stay on until it is no longer possible to collect energy. Timers were modeled for clear day cases only, since their operation is highly dependent on insolation pattern and timer delay.

The controllers are compared on the basis of their performance with respect to: collection efficiency, theoretical maximum steady-state efficiency, pump running time and pump cycling. The theoretical maximum efficiency is achieved with a controller which circulates fluid at a high rate that causes the collector temperature to equal the inlet temperature, whenever absorbed solar energy is greater than ambient losses.

Table I presents one day simulations of different control strategies indicating how their operation varies with different set points, timers, meteorological conditions, and flow rates. Additional results can be found in reference 13.

Collection Efficiency

For clear day cases the collection efficiency for all but one of the controllers is approximately equal and not more than 7% below the maximum steady-state efficiency. On/off controllers, in general, do slightly better, with on/off controllers with timers achieving the best efficiency since they run the pumps longer. It is doubtful that any type of controller could do better under similar conditions.

For low gain, clear day cases, excessive cycling of on/off controlled pumps can cause collection efficiency to be less with a high flow rate than with a low flow rate. Normally a higher flow rate leads to higher collection efficiencies; however, when a high flow rate causes excessive cycling the benefits can be outweighed by decreased circulation time.

During periods of interrupted insolation, neither proportional nor on/off controllers respond well to rapid changes in the insolation rate and the collection efficiency falls well below the maximum possible. Often this is because a significant portion of the incident energy can be collected only at temperatures less than those required to turn on the collector loop pump. However, proportionally-controlled collectors can collect more energy during such periods because of their increased sensitivity to changes in insolation and ambient temperature. This sensitivity also causes the proportional controller to maintain a lower average flow rate and thus operate the collector at higher temperatures. While decreasing collection efficiency, this may improve storage stratification and overall system performance.

In all high gain cases, clear and cloudy days, along with low gain, clear day cases any advantage a proportional controller has by turning on early is eliminated by lower average flow rates. For these cases on/off controllers with the same set points have similiar efficiencies. Only for low gain, interrupted insolation cases do proportional controllers show a clear advantage over on/off controllers.
Under these conditions, proportionally controlled systems were able to collect a higher percentage of the maximum steady- state efficiency of 26.5%. Neither type of controller though, is able to achieve efficiencies close to maximum steady-state efficiency; thus, improved controller design may be appropriate for climates where intermittent weather patterns predominate.

As can be seen in Table I, the on set point, ΔT_{on}, for an on/off controller can have a minimal effect on energy collection as long as it is not set so high that the collector pump does not come on until late in the morning. This is because the collector capacitance stores energy when the fluid is not circulating, energy which can be later released into the fluid. Because the collector acts as a storage device, low to moderate cycling of the pump also has a minimal effect on energy collection.

Dynamic effects of collector capacitance are important. Steady-state analyses tend to exaggerate the importance of cycling, ignore the effects of the turn on set point, and cannot consider cumulative solar input. Thus, steady-state predictions of the amount of heat transfered to the fluid during initial circulation is less than a dynamic model's prediction.

Another reason why the on point can have a minimal effect on energy collection is that the off set point actually determines when the circulating pump stays on. As indicated by the on/off controller with a perfect timer (equivalent to $\Delta T_{off} = 0$) the off set point should be set as low as possible to maximize collection time while meeting the requirements outlined previously.

The proportional controller set point for maximum flow also has an effect on energy collection. If this point is too high, the flow rate will never reach maximum and thus losses to ambient are increased. However, if the set point is too low, the proportional controller's sensitivity will be lost and the controller will act as a bang-bang controller.

<u>Pumping Time</u>

Parasitic energy usage is assumed equal to the product of pump motor power and pumping time. For proportional controllers an equivalent pumping time is calculated, since the pump is not always producing full flow. The effect of pumping time on collection efficiency is negligible for a typical collector array of 500 ft^2($46.5m^2$) with 0.1 horsepower(74.6 watt) pump. In all cases inclusion of pumping power does not change the ranking of any controller with respect to another; however, if a 0.5 horsepower(373 watt) pump is considered the effect of parasitic power does cause a slight change in rankings. For example, on/off controllers with `perfect` timers are no longer always the most efficient, since they run the pumps for an extended period of time.

Pump Cycling

Since pump cycling is considered a problem with on/off controllers, the number of times a collector pump cycles during one day has been indicated in Table I. Figure 3 shows a typical cycling sequence as predicted by the model. As expected pump cycling decreases with the use of higher on set points, lower off set points or proportional controllers. If cycling is minimal, collection efficiency will not be affected significantly since; 1) cycling will occur over a short increment of the total collection time and, 2) the collector will store energy when fluid is not circulating.

CONCLUSIONS

There are two implications of this study for the design and evaluation of proportional and on/off control. First, neither on/off nor proportional control performs best for all conditions. Whether on/off or proportional control should be implemented is dependent on local weather conditions and, perhaps more importantly, what set points are to be used with each type of controller. The advantages encountered with a proportional controller can be greatly offset by the proper selection of on/off controller set points.

Second, the difference between a steady-state and a dynamic analysis of control strategies is significant. Future work in modeling control systems must consider collector capacitance in order to accurately describe the transient response of the fluid temperature.

Additional work aimed at determining guidelines for the selection of appropriate control strategies and set points should include: 1) additional simulation studies using this or an improved dynamic solar system model which includes load loop dynamics, 2) experimental testing of the control strategies on facilities which can duplicate meteorological and load conditions for comparisons and 3) field tests. Experimental testing of control strategies is now under way at Lawrence Berkeley Laboratory by the authors.

ACKNOWLEDGMENTS

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COMPARISON OF PROPORTIONAL AND ON/OFF SOLAR COLLECTOR LOOP CONTROL STRATEGIES USING A DYNAMIC COLLECTOR MODEL: Schiller

Figure Captions for Figures and Tables

Figure 1: "Typical Solar Energy Collection System and Control Block Diagram"

Figure 2: "Temperature Loss in Pipes vs. Flow/Loss Factor * "

* Temperature loss in pipes is based on:

$$\dot{m}c(T_{in} - T_{out}) = (U_{pipe}\ L)[(T_{in} + T_{out})/2 - T_a]$$

** Typical domestic hot water system:

$\dot{m}c = 450$ W/ ^{o}C ; $U_{pipe} = 0.6$ W/m - ^{o}C

pipe length, L = 7.5 m

*** Typical heating system:

$\dot{m}c = 4500$ W/ ^{o}C ; $U_{pipe} = 0.6$ W/m - ^{o}C

pipe length, L = 37.5 m

Figure 3: " Outlet Fluid Temperature

Low Gain, Low Flow, Clear Day"

Table I: "CONTROLLER STRATEGY COMPARISONS 12 Hour Totals"

CONTROL STRATEGY		HIGH GAIN[a] HIGH FLOW[b] CLEAR DAY	HIGH GAIN LOW FLOW[c] CLEAR DAY	LOW GAIN[d] HIGH FLOW CLEAR DAY	LOW GAIN LOW FLOW CLEAR DAY	HIGH GAIN HIGH FLOW CLOUDY DAY[e]	HIGH GAIN LOW FLOW CLOUDY DAY	LOW GAIN HIGH FLOW CLOUDY DAY	LOW GAIN LOW FLOW CLOUDY DAY
Maximum Steady-State Efficiency(%)		65.7	65.7	39.5	39.5	56.1	56.1	26.5	26.5
ON/OFF On=9°F (5°C) Off=3°F(1.7°C)	efficiency(%)	60.3	59.6	35.0	34.9	45.2	45.2	8.6	8.5
	pumping time(hours)	8.72	9.27	2.76	5.98	3.34	3.83	.311	.496
	times cycled	10	2	61	10	14	12	4	10
ON/OFF On=21°F(11.7°C) Off=3°F(1.7°C)	efficiency(%)	59.7	59.1	31.9	33.9	44.1	44.2	5.2	5.4
	pumping time(hours)	8.39	8.98	1.39	5.44	2.47	2.92	0.095	0.16
	times cycled	6	2	22	6	12	18	2	2
ON/OFF With perfect timer On=9°F 5°C	efficiency(%)	60.5	59.9	35.7	35.3	--	--	--	--
	pumping time (hours)	9.87	9.88	7.68	7.69	--	--	--	--
	times cycled	0	0	0	0	--	--	--	--
ON/OFF With perfect timer On=21°F 11.7°C	efficiency(%)	60.4	59.8	35.5	35.1	--	--	--	--
	pumping time(hours)	9.71	9.72	7.38	7.39	--	--	--	--
	times cycled	0	0	0	0	--	--	--	--
PROPORTIONAL Full On=9°F 5°C Off = 3°F 1.7°C	efficiency(%)	60.2	59.7	35.0	34.7	45.4	45.0	9.6	9.5
	pumping time (equiv. hours)	7.54	8.85	3.58	4.63	3.20	4.03	0.52	0.72
	times cycled	0	0	0	0	0	0	0	0
PROPORTIONAL Full On=21°F 11.7°C Off = 3°F 1.7°C	efficiency(%)	59.6	59.0	34.4	33.9	44.8	44.3	9.4	9.1
	pumping time (equiv. hours)	4.92	6.33	2.34	3.01	2.16	2.84	0.38	0.51
	times cycled	0	0	0	0	0	0	0	0

a) high gain: insolation = 2292 BTU/ft^2-day
7224 watt-hrs/m^2-day
ambient temp. = 44.4° - 70°F
6.89° - 21.1°C

b) high flow = 25 lbm/hr-ft^2
122 kg/hr-m^2

c) low flow = 15 lbm/hr-ft^2
73.2 kg/hr-m^2

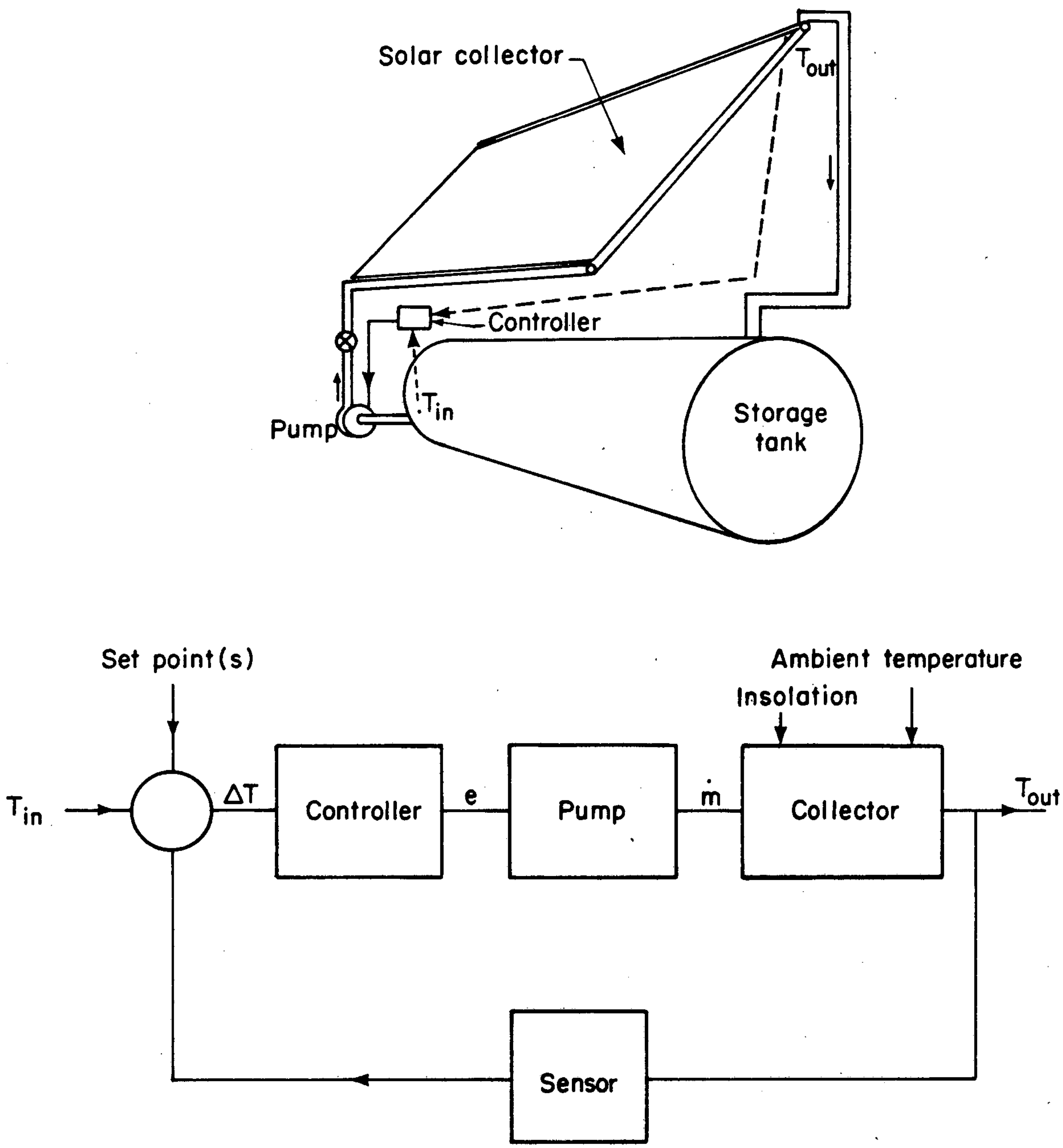
d) low gain: insolation=1146 BTU/ft^2-day
3612 watt-hrs/m^2-day
ambient temp.= 32.9° - 50°F
.5° - 10°C

inlet temperature = 115°F
46.1°C

collector capacitance = .7 BTU/ft^2-°F
14.3 kJ/m^2-°C

collector loss coefficient = .7 BTU/ft^2-hr-°F
3.97 watts/m^2-°C

e) for cloudy day cases, the total insolation is half of the clear day values given in (a) and (d)



TYPICAL SOLAR ENERGY COLLECTION SYSTEM AND CONTROL BLOCK DIAGRAM

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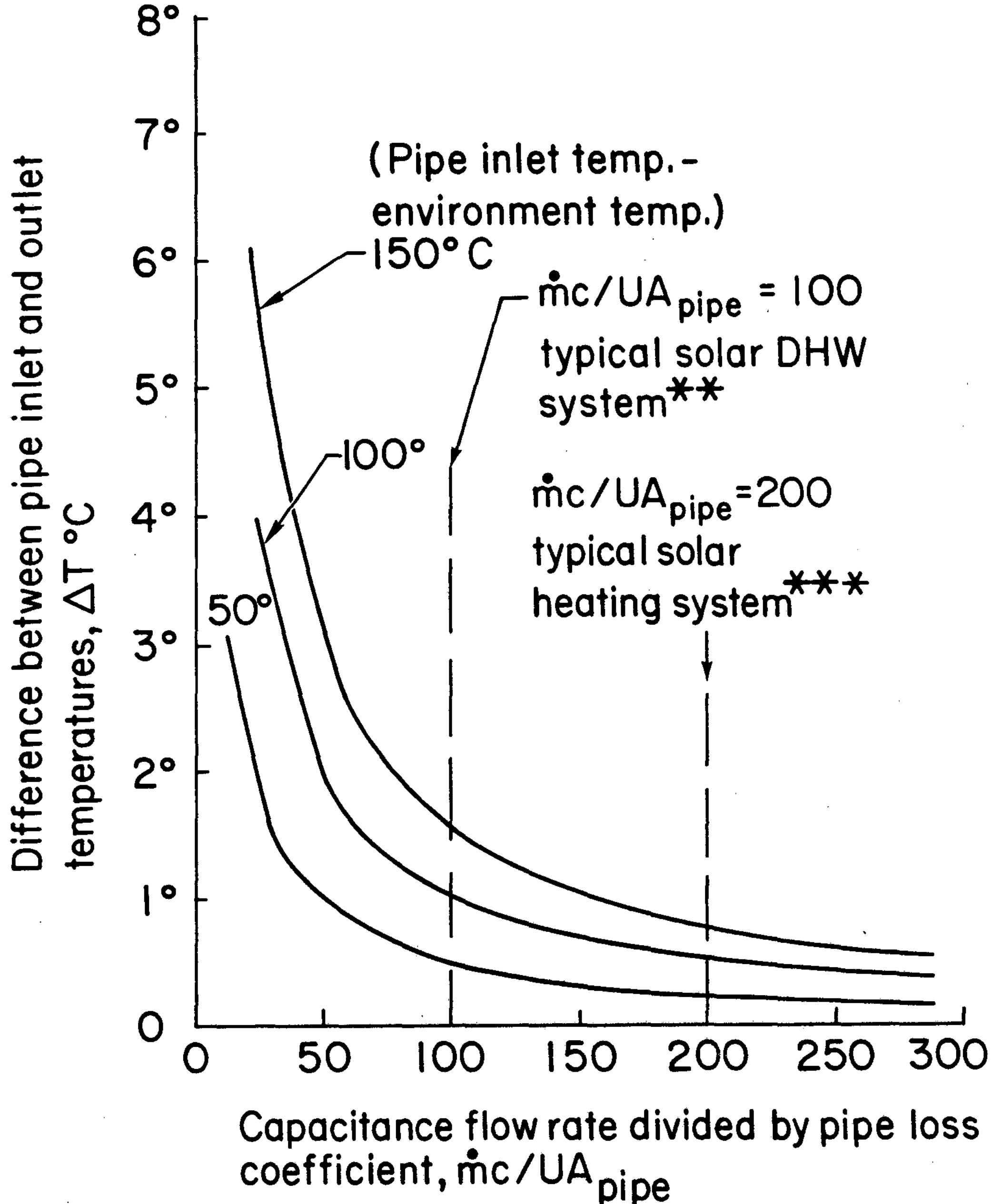
TEMPERATURE LOSS IN PIPES VS FLOW / LOSS FACTOR*



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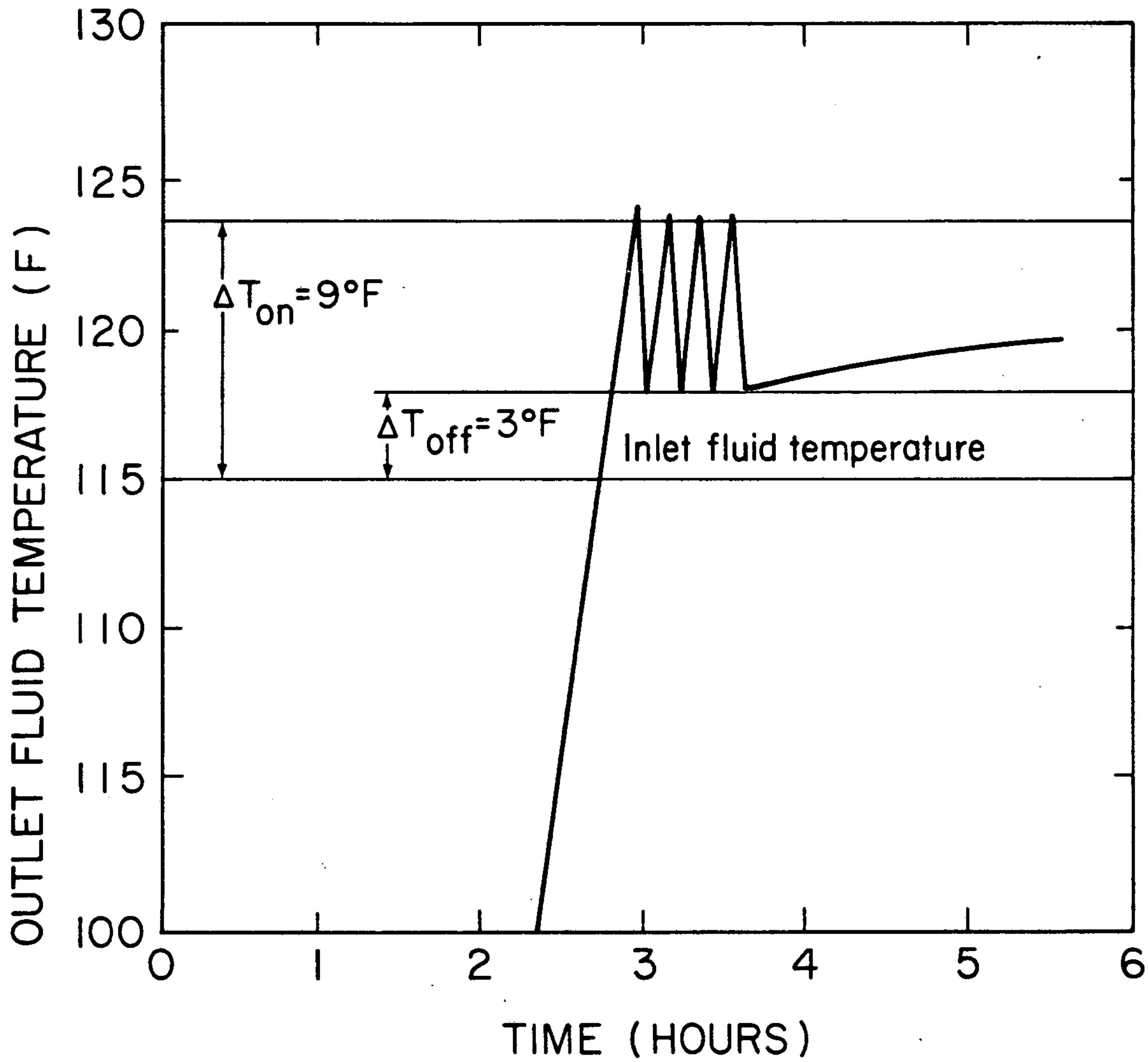

OUTLET FLUID TEMPERATURE
LOW GAIN, LOW FLOW, CLEAR DAY

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