PCL_DESIGN

PUMPED SOLAR COLLECTOR LOOP DESIGN

Design package to guide the selection of controller set points and pump flow rate for optimum solar collector loop output

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INTRODUCTION

The Pumped Collector Loop Design software package (PCL_Design) produces a stability map for the selected solar collector array, controller set points and pump flow rate. The controller stability is mapped in terms of inlet temperature (10°C to 80°C) and radiation intensity on the plane of the collector (50 W/m^2 to 1000 W/m^2). PCL_Design provides a map of the following collector loop factors

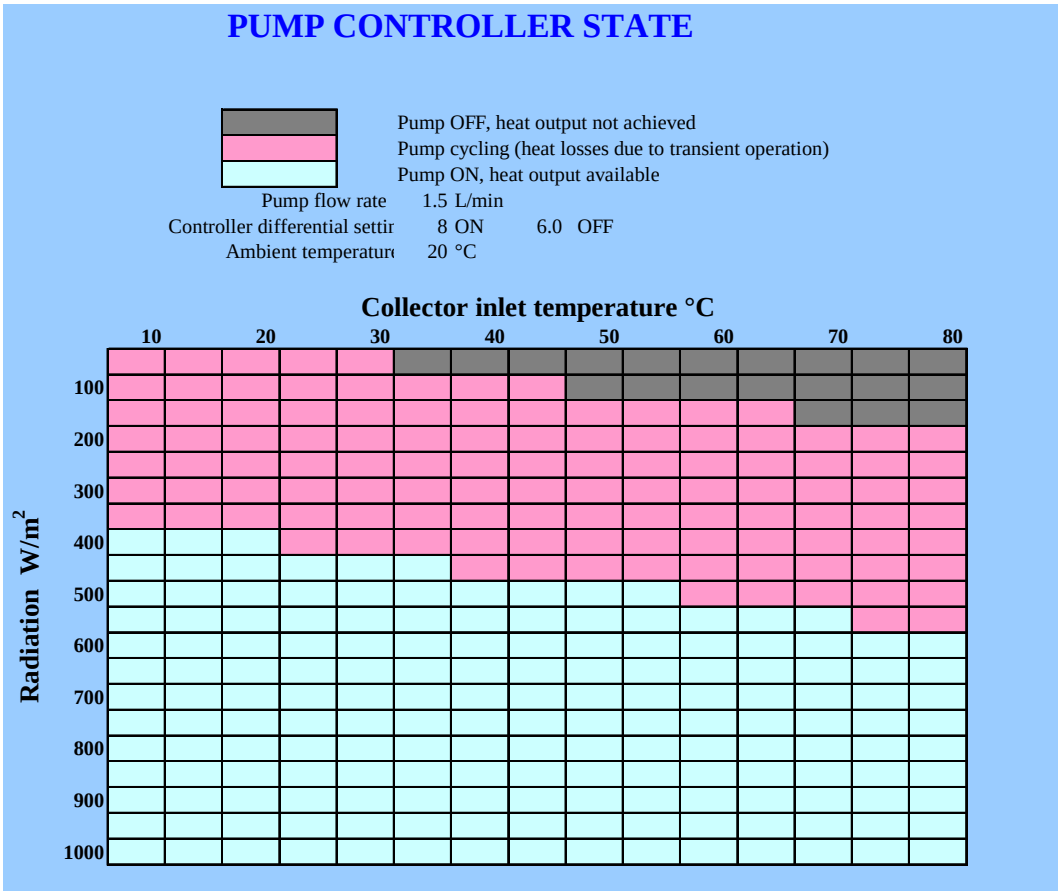
- Controller stability
- Collector loop temperature rise (collector temperature rise minus temperature drop across the connecting pipes)
- Heat delivered to the tank (collector heat gain minus piping heat loss)
- Collector loop temperature rise
- Return temperature to the tank from the collector loop
- Controller cycling times
- Collector stagnation temperature

SELECTION OF PUMP FLOW RATE AND CONTROLLER SET POINTS

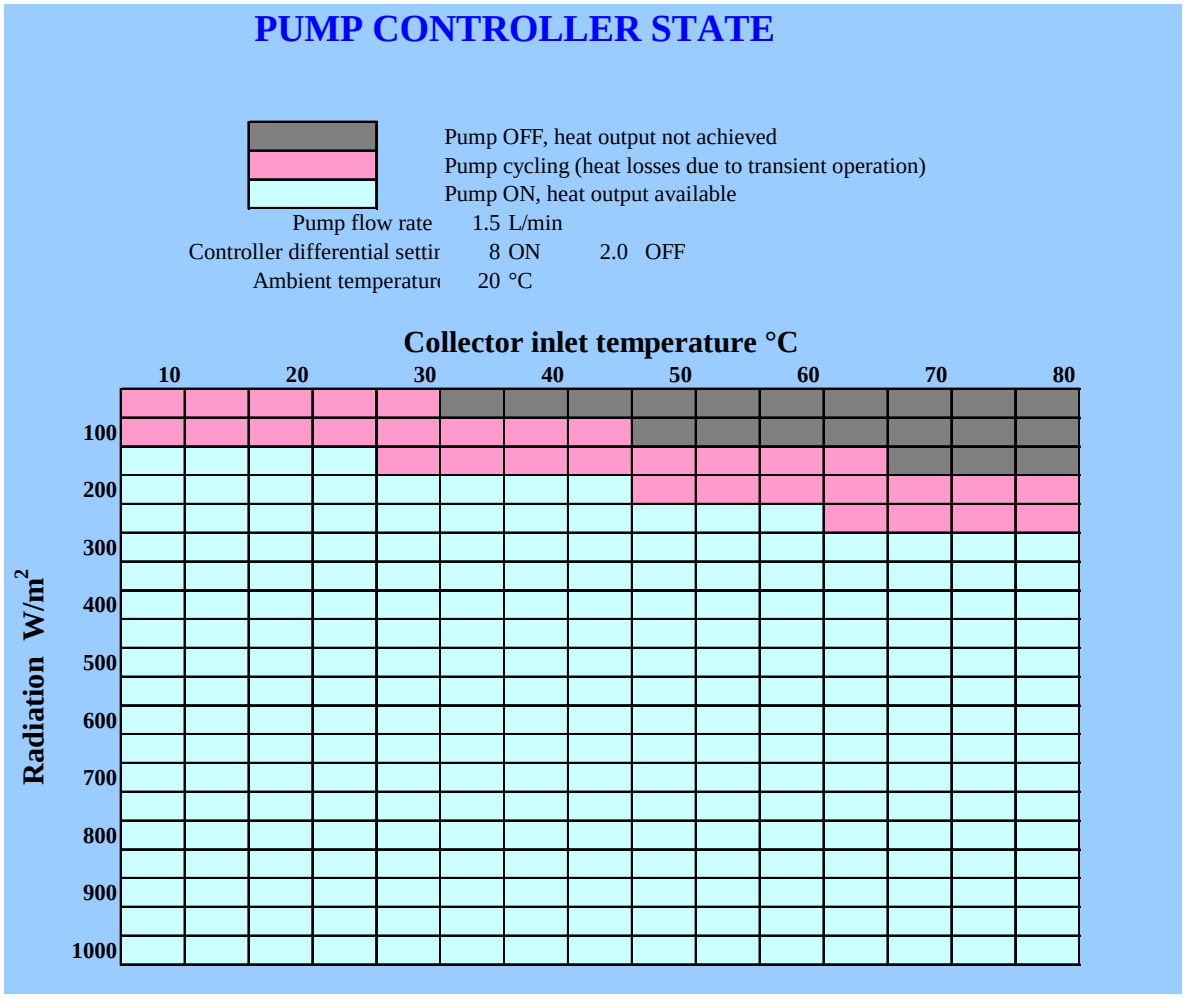
The most common pump controller is the fixed ΔT thermostat with hysteresis, which compares the collector outlet temperature and the temperature in the bottom of the tank. Selection of the controller turn ON and turn OFF temperature differences and the pump flow rate can have a significant effect on the performance of a pumped system. If the pump controller temperature difference settings are close eg 8/6 then the pump may turn ON/OFF most of the time except for very clear conditions.

Optimum specification of the controller temperature difference settings depends on the type of solar collector used. Evacuated tubes have a high stagnation temperature and hence can reach the turn ON temperature difference even in dull conditions, however the heat gain from the collector may not be sufficient to achieve a steady state temperature rise equal to the turn OFF temperature difference unless the sky condition is very clear. This means the pump runs until the heat is removed from the collector and then turns off and waits for the collector to reheat. The effect of this is to shunt hot water from the collector to the return pipe which then cools off while the controller waits for the collector to reheat.

In the controller performance map shown below the green area shows operating conditions (radiation intensity and collector inlet temperature) where the output of the collector is sufficient to achieve a steady temperature rise of more than 6K so the pump stays ON. The red zone shows conditions where the pump is turning ON/OFF and there are increased losses as a result. The dark area shows operating conditions where the pump is OFF.



The unstable zone of the controller can be reduced by lowering the turn OFF temperature differential setting or/and by reducing the flow rate. The pump operation map for the example collector array and controller settings of 8 ON / 2 OFF is shown below. The region of unstable pump operation is significantly reduced.



Further reduction of the unstable zone is possible by reducing the turn OFF difference setting, however if the turn OFF temperature difference is very small then there is the possibility of the pump running when the heat gain from the solar collector is less than the heat loss from the pipes connecting the solar collector to the tank. This can occur even though there is a positive temperature difference between the collector outlet and the bottom of the tank. For a controller turn OFF setting of 2 the net energy gain to the tank (collector heat output minus pipe losses) is shown in the following figure. A small zone of operation that results in net heat loss from the collector loop is circled. Reducing the turn off temperature difference setting further could result in some of the negative net heat gain areas moving into the stable pump controller zone.

COLLECTOR LOOP HEAT OUTPUT WHEN PUMP IS RUNNING
Watts

Pump OFF, heat output not achieved
Pump cycling (heat losses due to transient operation)
Pump ON, heat output available

Pump flow rate 1.5 L/min
Controller differential settin 8 ON 2.0 OFF
Ambient temperature 20 °C

Collector inlet temperature °C

Radiation W/m²	10	20	30	40	50	60	70	80
	156	116	77	37	-3	-44	-85	-85	-168	-210	-252	-295	-338	-381	-425
100	232	193	154	114	73	33	-8	-8	-91	-133	-176	-218	-261	-305	-349
	309	270	231	191	150	110	69	69	-15	-57	-99	-142	-185	-228	-272
200	386	347	307	267	227	186	145	145	62	20	-22	-65	-108	-152	-196
	463	424	384	344	304	263	222	222	139	97	54	11	-32	-75	-119
300	540	501	461	421	381	340	299	299	215	173	131	88	45	1	-43
	617	578	538	498	457	417	375	375	292	250	207	164	121	78	34
400	694	654	615	575	534	493	452	452	369	327	284	241	198	154	110
	771	731	691	651	611	570	529	529	445	403	361	318	274	231	187
500	848	808	768	728	688	647	606	606	522	480	437	394	351	307	263
	924	885	845	805	764	723	682	682	599	556	514	471	427	384	340
600	1001	962	922	882	841	800	759	759	675	633	590	547	504	460	416
	1078	1039	999	958	918	877	836	836	752	710	667	624	580	537	492
700	1155	1115	1076	1035	995	954	912	912	829	786	743	700	657	613	569
	1232	1192	1152	1112	1071	1030	989	989	905	863	820	777	733	690	645
800	1309	1269	1229	1189	1148	1107	1066	1066	982	939	897	853	810	766	722
	1386	1346	1306	1266	1225	1184	1142	1142	1058	1016	973	930	886	843	798
900	1462	1423	1383	1342	1302	1260	1219	1219	1135	1093	1050	1006	963	919	875
	1539	1500	1459	1419	1378	1337	1296	1296	1212	1169	1126	1083	1039	995	951
1000	1616	1576	1536	1496	1455	1414	1372	1372	1288	1246	1203	1160	1116	1072	1028

PUMP FLOW RATE AND TANK STRATIFICATION

The temperature rise achieved between the bottom of the tank and the flow returned to the tank governs the thermal stratification that can be achieved in the tank. Increased thermal stratification results in improved solar contribution. The collector loop temperature rise (temperature rise across the collector minus temperature drop along the connecting pipes) is an indication of the possible thermal stratification in the tank. A collector loop temperature rise of more than 20 K under clear sky conditions has been shown to produce improved system performance as a result of thermal stratification in the tank. For low flow rate systems small pipe diameters can be used in the collector loop and hence the pipe heat loss can be reduced.

PCL_Design provides a window into all of the factors effecting pumped solar collector loop operation. The primary feature of PCL_Design is the display of each factor in a matrix of inlet temperatures and solar radiation intensity so that the operation of the collector loop for all operating conditions can be seen in one output map. This allows design trade-offs to be made between the conflicting factors influencing optimum solar collector loop performance.

INPUTS

Solar collector loop parameters required as inputs to PCL Design are

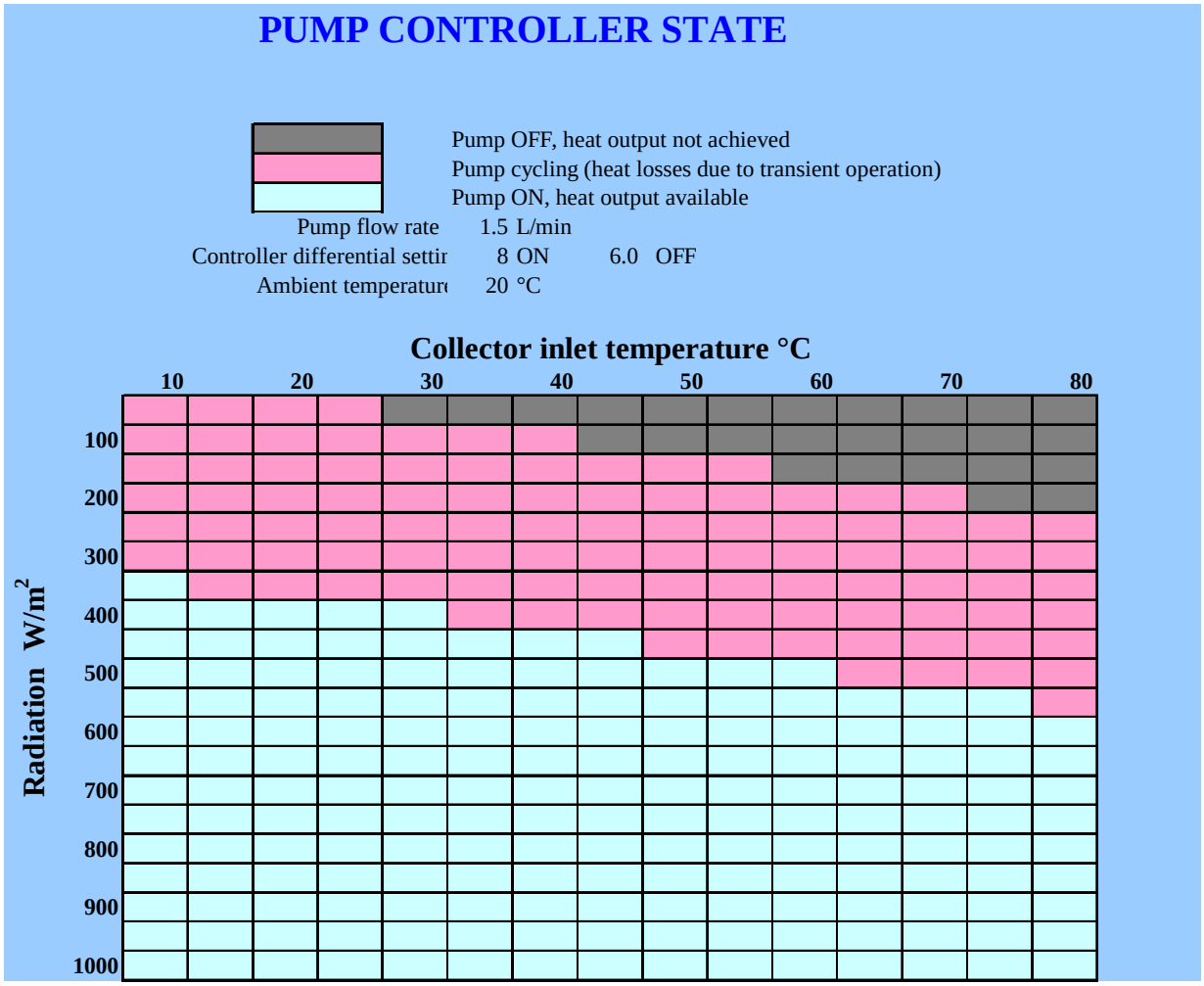
Solar collector efficiency	0.800	−	2.00	(Tm-Ta)/G	− 0.004	$(Tm-Ta)^2/G$
Solar collector aperture area	2	m^2				
Pump flow rate	1.5	L/min				
Controller differential settings	8	/	2	ΠνTonΠνToffΠ		
Ambient temperature	20	°C				
Pipe length tank to collector	10	m				
Pipe diameter	11	mm				
Pipe insulation thickness	10	mm				
Collector water content	1	kg				
Metal in contact with water	9	kg				
Metal type	Copper					
Glass content of collector	0	kg (zero for evacuated tube)				
Total thermal capacity	1.83	kg (H_2O)				

Solar collector efficiency coefficients from AS/NZS 2535 for aperture area
G = solar radiation W/m^2
Tm = average water temperature in solar collector °C
Ta = ambient temperature °C

OUTPUTS

The following output maps of solar collector loop performance are produced

PUMP CONTROLLER STABILITY



COLLECTOR LOOP HEAT OUTPUT

Net heat returned to the tank = collector heat output – piping heat loss

COLLECTOR LOOP HEAT OUTPUT WHEN PUMP IS RUNNING
Watts

Pump OFF, heat output not achieved
Pump cycling (heat losses due to transient operation)
Pump ON, heat output available

Pump flow rate	1.5	L/min		
Controller differential settir	8	ON	6.0	OFF
Ambient temperatur	20	°C		

Collector inlet temperature °C

Radiation W/m²	10	20	30	40	50	60	70	80
	156	116	77	37	-3	-44	-85	-85	-168	-210	-252	-295	-338	-381	-425
100	232	193	154	114	73	33	-8	-8	-91	-133	-176	-218	-261	-305	-349
	309	270	231	191	150	110	69	69	-15	-57	-99	-142	-185	-228	-272
200	386	347	307	267	227	186	145	145	62	20	-22	-65	-108	-152	-196
	463	424	384	344	304	263	222	222	139	97	54	11	-32	-75	-119
300	540	501	461	421	381	340	299	299	215	173	131	88	45	1	-43
	617	578	538	498	457	417	375	375	292	250	207	164	121	78	34
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500	848	808	768	728	688	647	606	606	522	480	437	394	351	307	263
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	1539	1500	1459	1419	1378	1337	1296	1296	1212	1169	1126	1083	1039	995	951
1000	1616	1576	1536	1496	1455	1414	1372	1372	1288	1246	1203	1160	1116	1072	1028

COLLECTOR LOOP TEMPERATURE RISE

Loop temperature rise = collector temperature rise – pipe line temperature drop

COLLECTOR LOOP TEMPERATURE RISE WHEN PUMP IS RUNNING (K)

Pump OFF, heat output not achieved
Pump cycling (heat losses due to transient operation)
Pump ON, heat output available

Pump flow rate 1.5 L/min
Controller differential settir 8 ON 6.0 OFF
Ambient temperatur 20 °C

Collector inlet temperature °C

Radiation W/m^2	10	20	30	40	50	60	70	80
	1.5	1.1	0.7	0.4	0.0	-0.4	-0.8	-1.2	-1.6	-2.0	-2.4	-2.8	-3.3	-3.7	-4.1
100	2.2	1.9	1.5	1.1	0.7	0.3	-0.1	-0.5	-0.9	-1.3	-1.7	-2.1	-2.5	-2.9	-3.4
	3.0	2.6	2.2	1.8	1.4	1.0	0.6	0.3	-0.2	-0.6	-1.0	-1.4	-1.8	-2.2	-2.6
200	3.7	3.3	2.9	2.6	2.2	1.8	1.4	1.0	0.6	0.2	-0.2	-0.6	-1.1	-1.5	-1.9
	4.4	4.1	3.7	3.3	2.9	2.5	2.1	1.7	1.3	0.9	0.5	0.1	-0.3	-0.7	-1.2
300	5.2	4.8	4.4	4.0	3.6	3.2	2.9	2.5	2.1	1.6	1.2	0.8	0.4	0.0	-0.4
	5.9	5.5	5.1	4.8	4.4	4.0	3.6	3.2	2.8	2.4	2.0	1.6	1.1	0.7	0.3
400	6.6	6.3	5.9	5.5	5.1	4.7	4.3	3.9	3.5	3.1	2.7	2.3	1.9	1.5	1.0
	7.4	7.0	6.6	6.2	5.8	5.5	5.1	4.7	4.3	3.8	3.4	3.0	2.6	2.2	1.8
500	8.1	7.7	7.4	7.0	6.6	6.2	5.8	5.4	5.0	4.6	4.2	3.8	3.3	2.9	2.5
	8.9	8.5	8.1	7.7	7.3	6.9	6.5	6.1	5.7	5.3	4.9	4.5	4.1	3.7	3.2
600	9.6	9.2	8.8	8.4	8.0	7.7	7.3	6.9	6.5	6.0	5.6	5.2	4.8	4.4	4.0
	10.3	9.9	9.6	9.2	8.8	8.4	8.0	7.6	7.2	6.8	6.4	6.0	5.5	5.1	4.7
700	11.1	10.7	10.3	9.9	9.5	9.1	8.7	8.3	7.9	7.5	7.1	6.7	6.3	5.8	5.4
	11.8	11.4	11.0	10.6	10.3	9.9	9.5	9.1	8.7	8.2	7.8	7.4	7.0	6.6	6.2
800	12.5	12.2	11.8	11.4	11.0	10.6	10.2	9.8	9.4	9.0	8.6	8.2	7.7	7.3	6.9
	13.3	12.9	12.5	12.1	11.7	11.3	10.9	10.5	10.1	9.7	9.3	8.9	8.5	8.0	7.6
900	14.0	13.6	13.2	12.8	12.5	12.1	11.7	11.3	10.9	10.4	10.0	9.6	9.2	8.8	8.4
	14.7	14.4	14.0	13.6	13.2	12.8	12.4	12.0	11.6	11.2	10.8	10.4	9.9	9.5	9.1
1000	15.5	15.1	14.7	14.3	13.9	13.5	13.1	12.7	12.3	11.9	11.5	11.1	10.7	10.2	9.8

COLLECTOR LOOP OUTLET TEMPERATURE

Loop outlet temperature = temperature returned to tank

COLLECTOR LOOP OUTLET TEMPERATURE (°C) WHEN PUMP IS RUNNING

Pump OFF, heat output not achieved
Pump cycling (heat losses due to transient operation)
Pump ON, heat output available

Pump flow rate 1.5 L/min
Controller differential settir 8 ON 6.0 OFF
Ambient temperatur 20 °C

Collector inlet temperature °C

Radiation W/m^2	10	20	30	40	50	60	70	80
	11.5	16.1	20.7	25.4	30.0	34.6	39.2	43.8	48.4	53.0	57.6	62.2	66.7	71.3	75.9
100	12.2	16.9	21.5	26.1	30.7	35.3	39.9	44.5	49.1	53.7	58.3	62.9	67.5	72.1	76.6
	13.0	17.6	22.2	26.8	31.4	36.0	40.6	45.3	49.8	54.4	59.0	63.6	68.2	72.8	77.4
200	13.7	18.3	22.9	27.6	32.2	36.8	41.4	46.0	50.6	55.2	59.8	64.4	68.9	73.5	78.1
	14.4	19.1	23.7	28.3	32.9	37.5	42.1	46.7	51.3	55.9	60.5	65.1	69.7	74.3	78.8
300	15.2	19.8	24.4	29.0	33.6	38.2	42.9	47.5	52.1	56.6	61.2	65.8	70.4	75.0	79.6
	15.9	20.5	25.1	29.8	34.4	39.0	43.6	48.2	52.8	57.4	62.0	66.6	71.1	75.7	80.3
400	16.6	21.3	25.9	30.5	35.1	39.7	44.3	48.9	53.5	58.1	62.7	67.3	71.9	76.5	81.0
	17.4	22.0	26.6	31.2	35.8	40.5	45.1	49.7	54.3	58.8	63.4	68.0	72.6	77.2	81.8
500	18.1	22.7	27.4	32.0	36.6	41.2	45.8	50.4	55.0	59.6	64.2	68.8	73.3	77.9	82.5
	18.9	23.5	28.1	32.7	37.3	41.9	46.5	51.1	55.7	60.3	64.9	69.5	74.1	78.7	83.2
600	19.6	24.2	28.8	33.4	38.0	42.7	47.3	51.9	56.5	61.0	65.6	70.2	74.8	79.4	84.0
	20.3	24.9	29.6	34.2	38.8	43.4	48.0	52.6	57.2	61.8	66.4	71.0	75.5	80.1	84.7
700	21.1	25.7	30.3	34.9	39.5	44.1	48.7	53.3	57.9	62.5	67.1	71.7	76.3	80.8	85.4
	21.8	26.4	31.0	35.6	40.3	44.9	49.5	54.1	58.7	63.2	67.8	72.4	77.0	81.6	86.2
800	22.5	27.2	31.8	36.4	41.0	45.6	50.2	54.8	59.4	64.0	68.6	73.2	77.7	82.3	86.9
	23.3	27.9	32.5	37.1	41.7	46.3	50.9	55.5	60.1	64.7	69.3	73.9	78.5	83.0	87.6
900	24.0	28.6	33.2	37.8	42.5	47.1	51.7	56.3	60.9	65.4	70.0	74.6	79.2	83.8	88.4
	24.7	29.4	34.0	38.6	43.2	47.8	52.4	57.0	61.6	66.2	70.8	75.4	79.9	84.5	89.1
1000	25.5	30.1	34.7	39.3	43.9	48.5	53.1	57.7	62.3	66.9	71.5	76.1	80.7	85.2	89.8

CONTROLLER CYCLE TIMES

COLLECTOR HEATUP TIME (min)

(Approx OFF time)

Flow transit time = 1.2 min (Approx ON time)

Pump OFF, heat output not achieved
Pump cycling (heat losses due to transient operation)
Pump ON, heat output available

Pump flow rate 1.5 L/min
Controller differential settir 8 ON 6.0 OFF
Ambient temperatur 20 °C

Collector inlet temperature °C

Radiation W/m²	10	20	30	40	50	60	70	80
	2.2 2.6 3.2 4.3 6.5	off off off off	off off off off	off off off off	off off off off	off off off off	off off off off	off off off off
100	1.3 1.4 1.6 1.9 2.2	2.6 3.3 4.5	off off off	off off off	off off off	off off off	off off off	off off off
	0.9 1.0 1.1 1.2 1.3	1.4 1.6 1.9	2.3 2.8	3.7	5.4	off	off	off
200	0.7 0.8 0.8 0.9 0.9	1.0 1.1 1.2	1.3 1.5	1.7	2.0	2.5	3.2	4.6
	0.6 0.6 0.6 0.7 0.7	0.8 0.8 0.9	0.9 1.0	1.1	1.3	1.4	1.6	1.9
300	0.5 0.5 0.5 0.6 0.6	0.6 0.7 0.7	0.7 0.8	0.8	0.9	1.0	1.1	1.2
	0.4 0.4 0.5 0.5 0.5	0.5 0.5 0.6	0.6 0.6	0.7	0.7	0.8	0.8	0.9
400	on on on 0.4 0.4	0.4 0.5 0.5	0.5 0.5	0.6	0.6	0.6	0.7	0.7
	on on on on on	on 0.4 0.4	0.4 0.5	0.5	0.5	0.5	0.5	0.6
500	on on on on on	on on on	on on	0.4	0.4	0.4	0.5	0.5
	on on on on on	on on on	on on	on	on	on	0.4	0.4
600	on on on on on	on on on	on on	on	on	on	on	on
	on on on on on	on on on	on on	on	on	on	on	on
700	on on on on on	on on on	on on	on	on	on	on	on
	on on on on on	on on on	on on	on	on	on	on	on
800	on on on on on	on on on	on on	on	on	on	on	on
	on on on on on	on on on	on on	on	on	on	on	on
900	on on on on on	on on on	on on	on	on	on	on	on
	on on on on on	on on on	on on	on	on	on	on	on
1000	on on on on on	on on on	on on	on	on	on	on	on

2 Ton/2 Toff

Specified 1.333
Stable 24.9 (linearised analysis)

COLLECTOR STAGNATION TEMPERATURE