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INVESTIGATION OF FLOW AND EFFICIENCY UNIFORMITY IN A DISTRIBUTED RECEIVER FIELD

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ABSTRACT

Uniformity of flow and collection efficiency within a distributed field of concentrating collectors have been evaluated experimentally. The results give a quantitative explanation for the nonuniformity among collector outlet temperatures which has been detected over years of system operation. Such temperature nonuniformity reduces system performance, and can cause degradation of heat transfer fluid.

This investigation was conducted on one row of five collectors of the 113 active parabolic dish collectors at the Solar Total Energy Project in Shenandoah, Georgia. Test results show significant nonuniformities in the optical, thermal and hydraulic performance among these collectors. These nonuniformities cause significant differences in the individual collector outlet temperatures.

Two alternative supply piping configurations were evaluated. Test results indicate that a reverse supply flow arrangement is preferred to the original direct flow piping. Installing reverse supply flow resulted in a 57% reduction in the standard deviation of the pressure drops across individual collectors. Also, a significant reduction in the standard deviation of the flows resulted.

INTRODUCTION

Temperature nonuniformity is a generic problem in distributed collector systems. It can degrade system performance, especially when maximum collection field temperature limits must be imposed to protect the heat transfer fluid. This report describes an experiment in which this nonuniformity was measured and the causes investigated. Pressure, flow, temperature and efficiency measurements are presented. Recommendations for design or operational improvements and implications for further research are discussed.

The Shenandoah Solar Total Energy Project (STEP) includes 113 parabolic dish collectors that individually track the sun (Figure 1). These collectors reflect sunlight into cavity-type receivers. A silicone-based heat transfer fluid (Syltherm 800, a product of Dow Corning) is heated from 260°C to 400°C (500°F to 750°F). Flow to all receivers is connected in parallel by a network of branch lines connected to main supply and return manifolds. Heat is supplied to a steam power cycle which supplies electricity, process steam and chilled water (via an absorption chiller) to an adjacent factory. The performance of this

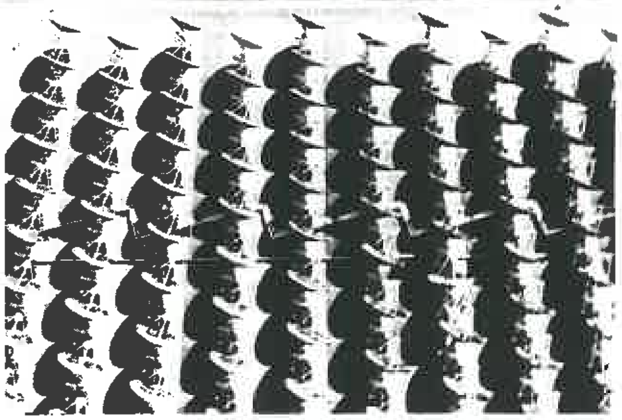


Fig. 1 The STEP collector field.

system is documented by Stine and Heckes (1988).

Past testing and operational experience has revealed nonuniformity in the heat transfer fluid outlet temperatures from the collectors. This is a problem because the heat transfer fluid leaving the field is not at the maximum capability of the field since the mixed heat transfer fluid in the manifold is at an average of the outlet temperatures.

This reduces system performance because the power cycle demands the highest outlet temperature possible for maximum conversion efficiency. Further, at STEP, the maximum operating temperature of the heat transfer fluid can not be exceeded because of fluid degradation problems. Therefore all receivers are operated at a lower temperature to prevent the hottest receiver from going over that limit. A third problem is that when a receiver does over-temperature, the collector is defocused. The receiver will continuously lose heat until operating personnel can go out into the field and 'valve-off' that collector.

Collector outlet temperature nonuniformity can result from at least three distinct causes;

1. Flow nonuniformity inherent in the design of the piping network.
2. Nonuniformity of collector efficiency caused by nonuniformity in their optical or heat transfer characteristics.
3. Flow restrictions within receivers.

EXPERIMENTAL PROCEDURE

A single row of five collectors was chosen for this investigation. The collectors are representative of the entire field except that there is difference in surface reflectance. The reflective surface of the collectors tested has been resurfaced with a silver film where aluminum film was originally applied. Reyes and Tench (1988) showed that this modification enhanced their collection efficiency by about 30%. However, it is safe to conclude that the results presented here are valid for the entire field because this investigation attempts only to make comparisons among the collectors in that row.

A second HTF supply line was installed with appropriate valving so the five collectors could be tested in both the original, first-in-first-out flow mode, and the last-in-first-out flow mode. This second mode is referred to here as the reverse supply mode. Reverse supply was used instead of reverse return because supply temperature is lower than return temperature and therefore, the added piping would lose less heat. Since the branch manifold lines at STEP are 'nested' in a single wrap of insulation as described by Stine and Heckes (1986), the third supply line was buried within this same envelope.

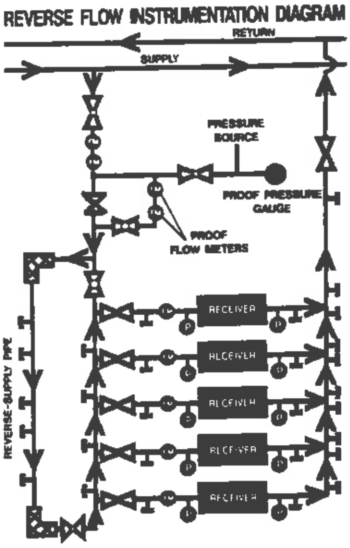


Fig. 2 Piping and instrumentation for reverse supply tests. Collector #406 is nearest the supply and return lines.

Each collector (collectors #406 through #410) was instrumented with a flow meter, pressure gages and immersion-type thermocouples. A schematic drawing of this instrumentation is shown in Figure 2. The instrumentation was designed to permit determining individual collector efficiencies and the hydraulic characteristics of the flow network. It was designed so relative calibrations of flow, temperature and pressure measurements could be performed during testing.

Instrument accuracies are given in Table I. The propagation of these uncertainties into the calculated efficiency, for the values used, is also given. Both flow and pressure transducers were calibrated relative to each other after installation since the purpose of this testing was to determine relative changes in these parameters. Although not quantifed, this procedure will increase their relative accuracy above the quoted absolute accuracies.

Table I - Instrumentation and Result Accuracy

Uncertainty:

Pressure: +/-6.9 or 7.9 kPa (1 or 1.5 psi)
Flow +/-0.095 l/min (0.025 gpm)
Temperature: +/-1.1^{o}C$_{2}$(2^{o}F)
Insolation: +/-12 W/m^{2}

Propagation of Uncertainty to Result:

Collector Efficiency: +/-0.018

Data were collected for 30 minute test periods, in 1 minute intervals. For each test a steady state period was selected that satisfied the criteria defined in Table II.

Table II - Stability Requirements for Steady-State Testing

Insolation Variation: +/-10 W/m^2
Inlet Temperature Variation: +/-1.7°C (3°F)
Outlet Temperature Variation: +/-2.2°C (4°F)

Test results were based on one representative data 'slice' within the steady state period. Tracking of the collectors and the pyrheliometer were checked throughout the 30 min test period.

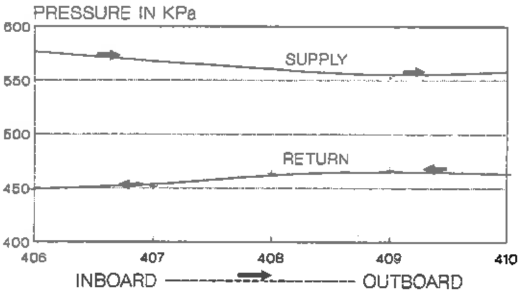
TEST RESULTS

Three experiments were performed to identify causes of temperature nonuniformity among collectors:

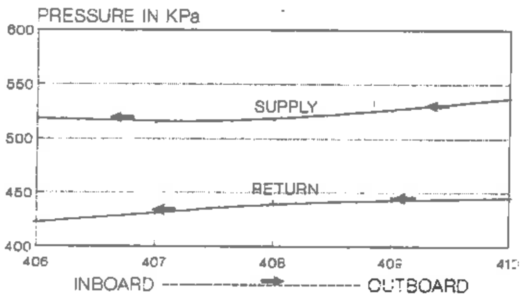
Reverse Supply Piping Effectiveness

The collector row was operated using both the first-in-first-out flow or 'direct supply' mode, and the last-in-first-out flow or 'reverse supply' mode. The pressure, flow, collector efficiency and temperature distributions were measured so the effects of this change in flow configuration could be quantified.

The pressure difference across each collector is shown in Figure 3a for the direct supply mode and in Figure 3b for the reverse supply mode. The reverse supply mode provides a marginal improvement in making the pressure differences across collectors equal. The effects of this change in pressure drop are shown in Table III.



a) direct supply



b) reverse supply

Fig. 3 Pressure profile for direct supply and reverse supply flow.

Table III - Standard Deviations of Selected Parameters - Percent of Average Values

Parameter	Direct Supply	Reverse Supply
Pressure Drop	14.6%	7.7%
Flow	5.7%	5.4%
Coll. Efficiency	4.9%	5.8%
Temperature Gain	5.2%	1.5%

Reverse supply flow reduced the standard deviation of the pressure differences by almost a factor of two. However, this reduction does not reflect itself in reducing the standard deviation of the flow to the individual collectors. Still, there is a significant reduction in the deviation of the outlet temperatures, the desired result.

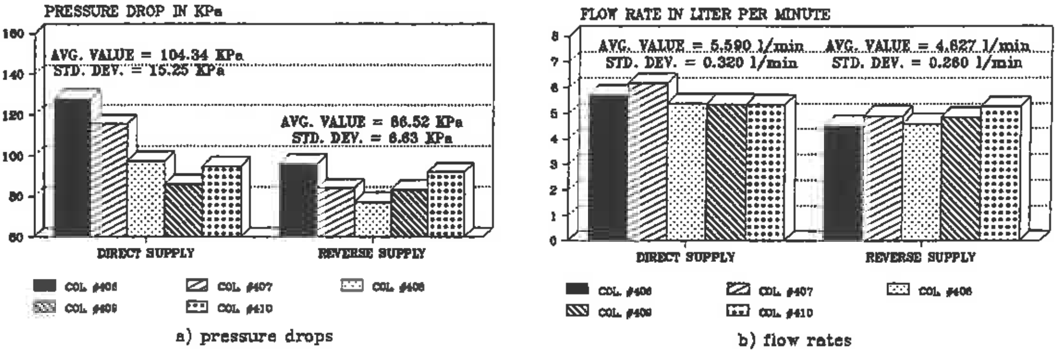
A more detailed study can be made by looking at the individual collector parameters as shown in Figure 4. Although the standard deviation of the flows was essentially the same for both flow configurations, their distribution changed. The collectors which had higher flow with direct supply piping (#406 and #407), had lower flow when the supply direction was reversed. However, since collector efficiencies remained essentially the same, the result was that the outlet temperatures increased on the two collectors for which the flow lowered. This increased their outlet temperatures and significantly reduced the standard deviation of their outlet temperatures.

Nonuniform Collector Thermal and Optical Performance

Flows to each collector in the row were equalized using the hand valves located in the inlet to each collector. With flow differences eliminated, optical/thermal performance variations could be determined from comparisons of temperature gains and efficiencies.

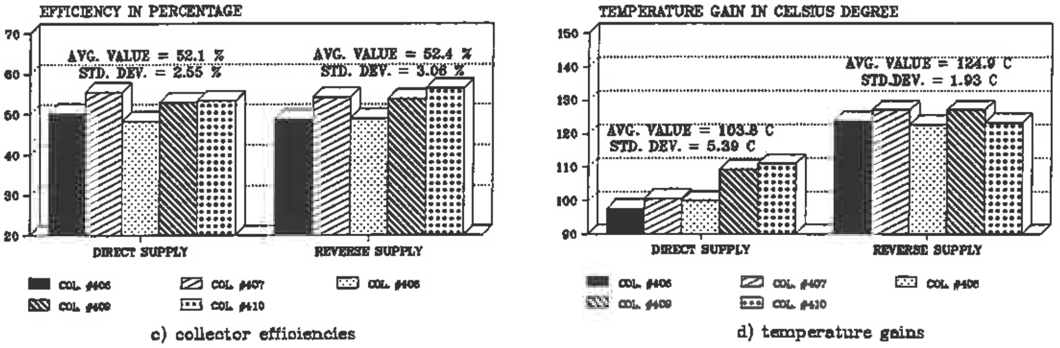
A comparison of the temperature gains for collectors #406 thru #410 are shown in Figure 5a for this balanced flow test. A variation in the temperature gain across the five collectors of 14.4°C (26°F) can be seen. Since flows are equal, this difference must be caused by factors affecting either the optical or thermal performance of the collectors.

Similar trends are seen by comparing collector efficiencies in Figure 5b. The maximum difference in collector efficiencies is 6.1%. For this test, the only explanation for the differences in outlet temperatures is collector-to-collector nonuniformity.



a) pressure drops

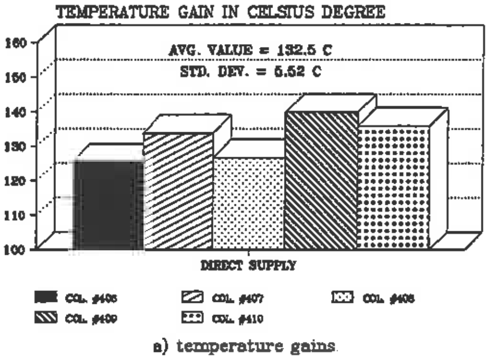
b) flow rates



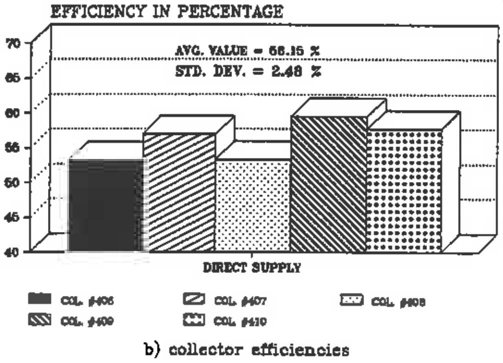
c) collector efficiencies

d) temperature gains

Fig. 4 Parameter distributions for direct supply and reverse supply flow.



a) temperature gains



b) collector efficiencies

Fig. 5 Comparison of parameter distributions for the equalized flow test.

Flow Curves

Pressure drops were recorded for each receiver for a range of flows with the inlet temperature held at 220°C (428°F). This is about the normal collector operating temperature. Flows were varied with a variable speed pump and the collectors were defocused to prevent overheating. Any variation in internal flow restrictions (clogging, kinks or manufacturing differences) can be recognized. These differences can be expected to play a role in producing nonuniformities in the fluid outlet temperatures.

Curves of receiver pressure drop vs. flow rate at 220°C (428°F) are shown in Figure 6. A calculated curve assuming smooth pipe is included for comparison. This figure indicates which receivers may have fouled tubing. Only the receiver on collector #406 shows a deviation from the predicted flow characteristics. This indicates there are internal flow restrictions in this receiver.

DISCUSSION

The task of evaluating direct and reverse supply flow configurations is complicated because the test collectors are not completely uniform. The results must

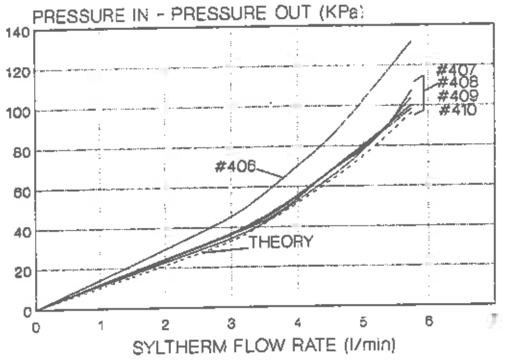


Fig. 6 Pressure loss characteristics of collectors at 220°C (428°F).

include an interpretation based on these differences. This section attempts to consider these individual collector differences.

Supply Flow Configuration

The design of the reverse supply piping network is not the ideal method of routing reverse supply, but was the most practical retrofit for this test. A better piping design for reverse supply piping is to route the main supply manifold on both outside margins of the collector array. The return manifold would run down the center.

Figure 4a shows that the extra piping installed for this test created added pressure drop and therefore reduced the overall flow to the test collectors. However, this did not affect the relative differences between collectors upon which this investigation is based.

Pressure Distribution

Probably the most convincing results advocating the preference to use reverse supply for improved flow uniformity are the pressure distribution measurements in Figure 3. The reverse supply shows a more desirable profile of pressure distribution and a lower standard deviation. Both pressure distribution profiles fit surprisingly well with theoretical expectations except the pressure drop measurement for collector #410 in direct supply.

In theory, the expected flow distribution should look similar to the results in Figure 3. In a pipe that does not include any branching of flow, the pressure decreases linearly along the flow. In a pipe that includes branching of flow like these manifolds, the rate of pressure change will vary as flow is separated or combined.

Since the supply manifold flow decreases at every branch, the pressure drop with length decreases. The result is a pressure profile that is concave upwards as shown in Figure 3. Return manifold flow increases at every branch resulting in a pressure profile that is concave downwards as shown.

A slight error in the inlet and outlet pressure measurement on collector #410 can be noted. This explains the increases in pressure along the flow in both the supply and return manifolds between collectors #409 and #410. Probably, the inlet pressure measurement is too high and the outlet pressure too low. These probable errors combine to show an erroneously high pressure drop.

Another noticeable measurement error is in the inlet pressure of collector #406 in reverse supply mode. Here the reading appears to be high so the pressure drop correspondingly is too high.

Considering these errors, and the pressure measurement uncertainty, a more accurate evaluation of Figure 4a can be made. It is reasonable from Figure 3 to assume that the pressure difference at collector #410 in the direct supply mode could be about 17 kPa (2.47 psi) less, and at collector #406 for the reverse supply mode, 7 kPa (1.02 psi) less. This would result in a significant decrease in the standard deviation for reverse supply and an increase for direct supply. It is concluded that the effect of reverse supply flow on providing uniform pressure drops is even more dramatic than shown by the measured data.

Flow Uniformity

The flow distribution in Figure 4b shows an improvement in flow uniformity for reverse supply instead of direct supply. The improvement is, however, very slight and a larger improvement was expected due to the improved pressure distribution. This discrepancy can be explained by the flow restriction noted in collector #406 which was described in Figure 6. With an unrestricted collector at this position, an increased variation in flow for direct supply and decreased variation for reverse supply should result.

Temperature Uniformity

A careful analysis of the temperature gain distribution reveals that the results are somewhat misleading. Figure 5a is representative of the temperature gain distribution under an almost perfect flow distribution. The standard deviation of 5.52°C (9.94°F) for this test is the minimum uniformity that a near perfect flow network could provide for these collectors (with varying optical/thermal efficiencies).

However, Figure 4d shows that reverse return flow significantly decreases the deviation in temperature rises. The standard deviation decreases from 5.39 to 1.93°C (9.70 to 3.47°F). This would seem impossible since there is little change in the standard deviations of the flows as is seen in Figure 4b.

An explanation for this anomaly is that changing to reverse return flow redistributes the flows (although not changing their standard deviation). Flows to the collectors with lower efficiency (#406 and #408) were reduced resulting in higher temperature gains. If all of the collectors had the same optical/thermal efficiency, the change in temperature gain distribution would have been equivalent to the change in flow distribution.

A possible indicator that reverse supply improves temperature gain uniformity can be seen by comparing the profile of Figure 5a (the equalized flow test) with Figure 4d (the unrestricted flow test). This comparison shows that temperature rises for the equalized flow case are similar to those for the reverse return, full flow case. This further shows the ability of the reverse return flow configuration to balance outlet temperatures of the individual collectors.

Efficiency Uniformity

Only a small change in efficiencies is expected for both flow conditions. This is because changes in temperature gains offset changes in flow rates. The net result is a negligible change in efficiency. This argument assumes that temperature gains are small enough so collectors do not experience differences in heat loss due to second order effects.

Comparisons of the efficiency distributions in Figures 4c and 5b show that measurements were good because similar profiles were obtained. The differences in standard deviations are small and largely caused by measurement errors propagated into the efficiency from measured values.

However, the average levels were higher for the equalized flow test. The higher average efficiency of the equalized flow test was due to higher insolation and lower receiver operating temperatures during this test. This conclusion is based on previous collector efficiency tests described by Gastelum (1986).

CONCLUSIONS AND RECOMMENDATIONS

These experimental results support a preference for the reverse supply configuration in distributed-receiver solar collector piping networks. The measured improvement in flow uniformity is in accord with theoretical projections. While marginal, this improvement could be crucial in installations where the heat transfer fluid is heated near its temperature limit.

Optical and thermal performance variations among collectors are significant and must be allowed for in array design and flow balancing.

Flow resistance differences, at least among collectors after exposure to temperature excursions, can be different enough to dominate the flow distribution. The resulting reduced flow will cause further temperature excursions unless flow is increased in the entire row to lower its average outlet temperature.

Continuation and replication of the current testing is recommended. In particular, the pressure measurement anomalies should be alleviated, possibly with the use of differential pressure transducers. Further testing with clean receivers is also recommended.

Related testing to distinguish the effects of optical and thermal performance on collector efficiencies and the importance of second-order flow rate effects on efficiency is also recommended.

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