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INITIAL COMPARISONS OF SOLAR COLLECTOR PERFORMANCE DATA OBTAINED OUT-OF DOORS AND WITH A SOLAR SIMULATOR

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ABSTRACT

A facility was constructed to evaluate solar collector performance outdoors for condititions that would be encountered by collectors if they were incorporated in a solar heating/cooling system. In addition to obtaining initial collector performance data, the outdoor facility will enable collector durability and degradation rates to be evaluated for operating periods of several months. The data obtained from the outdoor tests were compared to collector performance predicted on the basis of results obtained with a solar simulator. The performance measured outdoors was less than the predicted performance.

E-8472

INTRODUCTION

A program is being conducted at NASA-Lewis Research Center to develop the technology for efficient, reliable, low-cost solar collectors. A summary of the technology program is presented in references 1 and 2 along with a description of a solar-heated and cooled energy-conservative office building being constructed at NASA's Langley Research Center. The Lewis technology program will provide the basis for selecting collectors for use on the energy-conservative building at Langley. The collector technology program includes identifying, investigating, and evaluating the factors that affect collector performance including: absorber materials and coatings (selective and non-selective), number and material of covers, thermal insulation, and anti-reflecting treatment for covers. This inhouse program was augmented by a contract with Honeywell, Inc., "Development of Flat Plate Solar Collectors for the Heating and Cooling of Buildings", Contract No. NAS 3-178620.

An important phase of this collector technology program is the experimental evaluation of collector performance. Two methods are employed. One utilizes a solar simulator indoors where collectors are evaluated, one at a time, under known controlled conditions that can be readily repeated. The second method consists of testing up to ten collectors simultaneously outdoors.

There are advantages and disadvantages to each of these methods. Indoor testing permits large numbers of collectors to be readily evaluated under identical conditions. A mathematical model is needed to predict outdoor performance on the basis of performance determined with the solar simulator (ref. 3). Simultaneous operation of several collectors outdoors permits evaluation and comparison of performance under conditions similar to those encountered by collectors operating in solar systems. Because of the exposure time required to determine environmental effects, however, the capability to test large numbers of collectors rapidly outdoors is limited.

References 4 through 7 present collector performance data determined with the solar simulator, which has been in operation for a year and a half. The outdoor facility was just completed in the spring of 1975. The purpose of this paper is to present performance data for collectors tested outdoors to date, and to compare those experimental values to the predicted performance based upon results obtained using the solar simulator. A brief description of the outdoor test facility is included.

DESCRIPTION OF FACILITY

A photograph of the facility is presented in figure 1 and a simplified schematic of the flow loop is shown in figure 2. The facility is composed of two separate flow systems, each having a capability of operating five collectors in parallel. The liquid coolant is a 50-50 mixture, by weight, of ethylene glycol and water. The ethylene glycol was purchased with inhibitors (table I). A commercial fiberglass-lined water heater with the magnesium sacrificial anodes removed provides a storage capacity of 80 gallons. Two electric immersion heaters in this water tank provide a ready means of raising the temperature of the entire liquid inventory. A centrifugal pump driven by a 1/4-horsepower electric motor circulates the liquid. A filter, 25 micron particle size, provides continuous filtration of the liquid. A conventional air-liquid heat exchanger, with an on-off control, is used to reject energy when desired.

Aluminum screen was placed in the flow path upstream of each collector having aluminum in contact with the glycol-water mixture. High-temperature rubber hoses were used to connect the inlet and outlet of each collector to the flow loop to minimize galvanic corrosion. The flow through each collector is manually adjusted with a remotely operated valve. The flow rate through the collector by-pass line is controlled to maintain a constant pressure in the collector inlet manifold. Thus, when the flow rate through one collector is varied, the flow through the remaining collectors remains constant with no adjustment of the flow-control valves. Auxiliary heaters with electric immersion elements are located at the inlet of each collector. These heaters provide a controlled variation of inlet temperature from collector to collector. The liquid discharge from the collectors is returned to the storage tank. An expansion tank accommodates volume changes of the liquid inventory.

The instrumentation is summarized in figure 3. The liquid flow rate through each collector is measured with a turbine-type flowmeter. The flowmeters were calibrated with the same type of liquid as used in the system, i.e., 50-50 mixture of ethylene-glycol and water. The flowmeters operate on the principle of variable reluctance, as opposed to having magnetic pickups, to minimize the drag on the turbine wheel. The variable reluctance flowmeter can therefore be used to measure smaller flow rates than the flowmeters incorporating magnetic pickups.

The various collector temperatures were measured with chromel-constantan thermocouples, ISA type E. The inlet and outlet thermocouples were made from the same spool of wire. All thermocouples were calibrated in an oil bath, and then the inlet and outlet thermocouples were matched to provide minimum error in the temperature measurement.

For the data reported herein the total solar flux was measured only in the plane of the collectors. The output of the pyranometer was continuously integrated using electronic equipment. Additional instrumentation was installed recently to measure the total solar flux in a horizontal plane, the direct or beam radiation, and also the diffuse radiation in a horizontal plane.

The recent acquisition of additional pyranometers permitted comparison of simultaneous measurements of solar flux. The pyranometer used for the data reported in this paper indicated a maximum difference of 15 percent in total flux when the simultaneous measurements were compared. The comparisons indicated that the pyranometers were sensitive to both the angle of incidence of the direct radiation and azimuth orientation of the pyranometer. The instantaneous solar flux values measured for the data reported herein have possible errors on the order of 15 percent.

In addition to the collector and insolation data the following weather data were recorded: air temperature, wind speed and direction, and relative humidity.

DISCUSSION OF RESULTS

The collectors were mounted facing south and were tilted to an angle of 60 degrees with respect to horizontal plane. On a given day the collector tests were conducted at constant flow rate and constant inlet temperature. The nominal test flow rate was 10 lbm/hr/ft^2, based upon the absorber area. Collector efficiency is essentially independent of flow rate at that value. After the desired collector inlet temperature was obtained and the outlet temperature stabilized, data were recorded at 4-minute intervals. "Clear day" performance for the five collectors tested outdoors is presented in figure 4. The instantaneous data are presented for incident angles up to 30 degrees. The performance of each collector as determined with the simulator (simulated solar flux normal to collector) is also presented. The instantaneous efficiency,

$$\eta = \frac{\dot{m} C_p (T_{out} - T_{in})}{q_{solar} A_{abs}}$$

is plotted as a function of the ratio

$$\frac{T_{in} - T_{amb}}{q_{solar}}$$

This format is particularly useful when employing the collector performance parameters presented by Hottel, Whillier, and Bliss in references 8 and 9. They express the collector efficiency as:

$$\eta = F_R \left[\alpha\tau - \frac{U_L (T_{in} - T_{amb})}{q_{solar}} \right].$$

The intercept on the ordinate is a function of the absorptance of the absorber, α, and transmittance of the cover system τ. The slope of the data is a function of the overall heat loss coefficient, U_L.

The intercept at ($\Delta T/q = 0$ for the outdoor data is lower for all collectors than the values obtained with the simulator. Also, the slope of the outdoor data is generally greater than the slope of the data obtained indoors. The factors that affect collector performance include: wind speed, angle of incidence of the insolation, the ratio of diffuse to total radiation, tilt angle, ambient temperature, and effective sky (sink) temperature. The wind speeds were not significantly different, 2-15 mph outdoors and 7 mph indoors. The effect of incident angle was minimized by limiting the outdoor data to angles less than 30 degrees. At an angle of incidence of 30 degrees the energy transmitted by the cover system would be reduced less than 5 percent compared to normal-incidence transmission. On a clear day when the diffuse radiation is about 10 to 20 percent of the total, the amount of diffuse radiation should not reduce collector performance more than 5 percent. The tilt angle of the collectors was not significantly different; 60 degrees outdoors and 57 degrees indoors. In addition to these small effects, differences in the collector performance, apparent when comparing the data obtained indoors and outdoors, could be due to the effective sky (sink) temperatures and the different ambient temperatures. Except for six data points recorded for two collectors, the outdoor data were obtained at ambient temperatures between 30° F and 50° F while the indoor data were obtained at 85° F. The ambient temperature effect is most pronounced for collectors with selective absorbers operating at low temperatures.

There is always the possibility that properties of the absorber coatings could have changed during operation outdoors. A decrease in absorptance would reduce the intercept at $(\Delta T)/q = 0$, and an increase in emittance would result in increased heat losses and greater slope to the data. If water, either from condensation or rain, had accumulated in insulation beneath the absorber the heat loss outdoors would be larger than indoors. When the collectors are removed from the outdoor facility they will be tested indoors to determine any change of performance.

There are several methods that can be employed to modify either the indoor or outdoor data for a more direct comparison. The approach chosen for this report uses the method proposed by Simon in reference 3 to predict outdoor performance on the basis of data obtained with the simulator. This approach is useful for predicting hour-by-hour and day-long performance for a variety of conditions on the basis of readily obtained, controlled test conditions.

A comparison of the performance predicted by this method (ref. 3) using data measured in the simulator, and the actual performance measured outdoors is presented in table 2. The predictions consist of a single calculation for each hour and are based upon the insolation measured outdoors for each hour, the average ambient temperature for each hour, and angle of incidence at the midpoint of each hour. The outdoor data was based upon the energy absorbed by the collector coolant and the measured insolation for each hour. The difference in predicted and measured performance for the hours of 9 a.m. to 4 p.m. solar time varied from 2 to 10 percentage points. The performance measured outdoors was always lower than the predicted performance. It is planned that some or all of these collectors will be re-evaluated in the indoor facility to determine any degradation resulting from outdoor operation. It should be obvious that the whole story is not yet in regarding differences between solar collector behavior under simulated, laboratory conditions and under outdoor conditions. More work is needed.

The predicted and measured performances agreed more closely near solar noon than early and late in the day. The deviations at the beginning and end of the day are partly due to the pyranometer error which increased with increasing angle of incidence. The pyranometer error wasn't large enough to explain the entire difference, however.

In addition to the foregoing general results, an incident occurred that is worth mentioning. A mylar honeycomb was installed in a collector supplied by Honeywell, Inc. The collector had an aluminum roll-bond absorber painted with black paint (3 M Nextel) and two glass covers. The mylar honeycomb had an effective cell diameter of 3/8 in. and a cell length of 5/8 in. Before significant data could be obtained, however, the flow loop was automatically shutdown during a weekend of clear skies. The no-flow condition in the collector resulted in high absorber temperatures that caused a deformation of the honeycomb, as shown in figure 5. The no flow condition in clear weather has also resulted in broken inner glass covers in some of the two-cover collectors. This result illustrates the need to design for various operating conditions instead of a simple design point.

CONCLUDING REMARKS

Solar collectors have been tested both indoors with a solar simulator and more recently outdoors at Lewis Research Center. Instantaneous data were presented in this report for 5 collectors tested outdoors, and the outdoor data is compared to data previously obtained indoors. The instantaneous efficiency measured outdoors was always found to be less than the efficiency measured indoors. The differences could be due both to test condition differences and to changes in collector characteristics. Hour-by-hour and day-long performances measured outdoors were compared to performances predicted on the basis of the indoor tests. The day-long performance measured outdoors was consistentently from 2 to 10 percentage points below the predicted values. The reasons for the differences remain to be determined.

SYMBOLS

A_{abs}	Area of absorber, ft^2
C_p	Specific heat of fluid, Btu/lb ^oF
F_R	Overall collector plate heat removal factor, dimensionless
q_{solar}	Total flux in plane of collector, Btu/hr/ft^2
$\dot{m}$	Fluid mass flow rate, lb/hr
T_{amb}	Ambient air temperature, ^oF

T_{in}	Fluid temperature at collector inlet, ^{o}F
T_{out}	Fluid temperature at collector outlet, ^{o}F
U_L	Overall heat loss coefficient, $Btu/hr/ft^2/^{o}F$
α	Absorptance of collector absorber, dimensionless
η	Collector efficiency, dimensionless
τ	Transmittance of collector cover system, dimensionless

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TABLE I. - INHIBITORS IN ETHYLENE-GLYCOL

	Composition by weight, percent
Trisodium phosphate, calculated as dodecahydrate	0.30±0.04
Borax (sodium tetraborate, decahydrate) [illegible]-535, Type II	4.00±0.20
sodium salt of mercaptobenzothiazole, 50% aqueous solution, by weight	0.40±0.05

E-8472

TABLE II. - COLLECTOR PERFORMANCE FOR JANUARY 24, 1975

[$T_{in} \sim 110^{\circ}$ F, wind 2-15 mph.]

Solar time period	Total insolation Btu/ft^2	T_{amb} ^{o}F	Collector efficiency (percent)									
			LeRC 1		Beasely Solorpack 2		Honeywell/LeRC black nickel 3		MSFC black nickel 4		Honeywell/LeRC black paint 5	
			P*	M*	P	M	P	M	P	M	P	M
9-10 a. m.	223	45	47	32	35	27	50	39	32	26	47	40
10-11 a. m.	274	46	54	42	40	35	56	47	37	33	53	48
11-12 p. m.	293	46	56	45	42	40	57	52	39	37	55	53
12-1 p. m.	287	48	56	50	42	43	57	54	39	39	55	56
1-2 p. m.	246	50	54	49	40	38	56	54	37	37	53	54
2-3 p. m.	212	51	48	34	35	31	51	41	32	29	47	43
3-4 p. m.	136	51	29	21	18	16	34	29	18	16	28	26
Overall	1671	--	51	41	38	35	53	47	35	32	50	48

*P = Predicted from simulator data.

M = Determined outdoors.

Figure 1. - Outdoor collector facility.

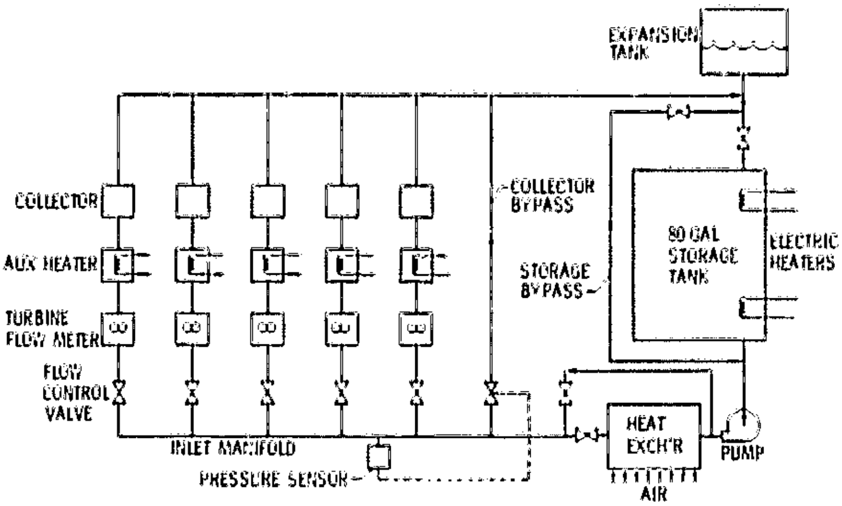

Figure 2. - Schematic of outdoor collector facility.

- COLLECTOR
  - FLOW RATE
  - TEMPERATURE
    - IN
    - OUT
    - PLATE
    - GLASS
  - PRESSURE
    - IN
    - DELTA P
- SOLAR FLUX
  - TOTAL IN PLANE OF COLLECTOR
  - TOTAL HORIZONTAL
  - DIFFUSE HORIZONTAL
  - DIRECT

Figure 3. - Instrumentation for outdoor collector tests.

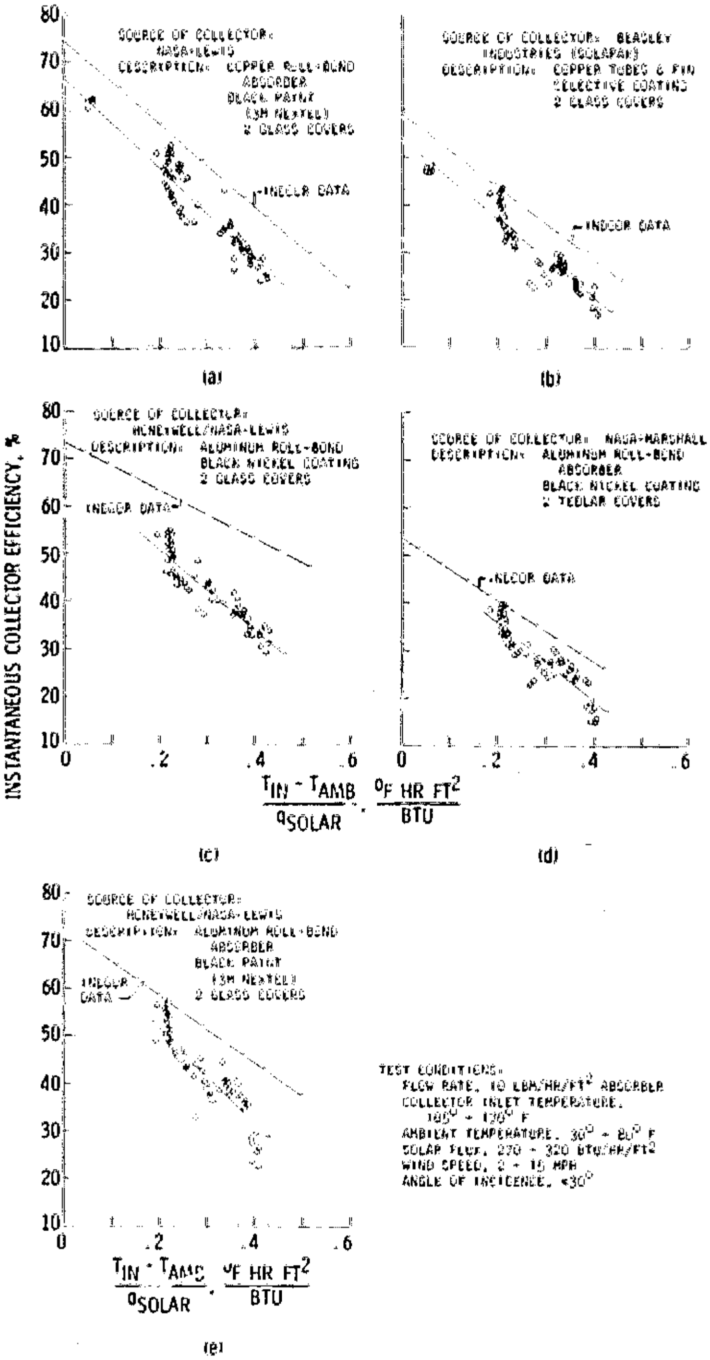

Figure 4. - Instantaneous collector performance.

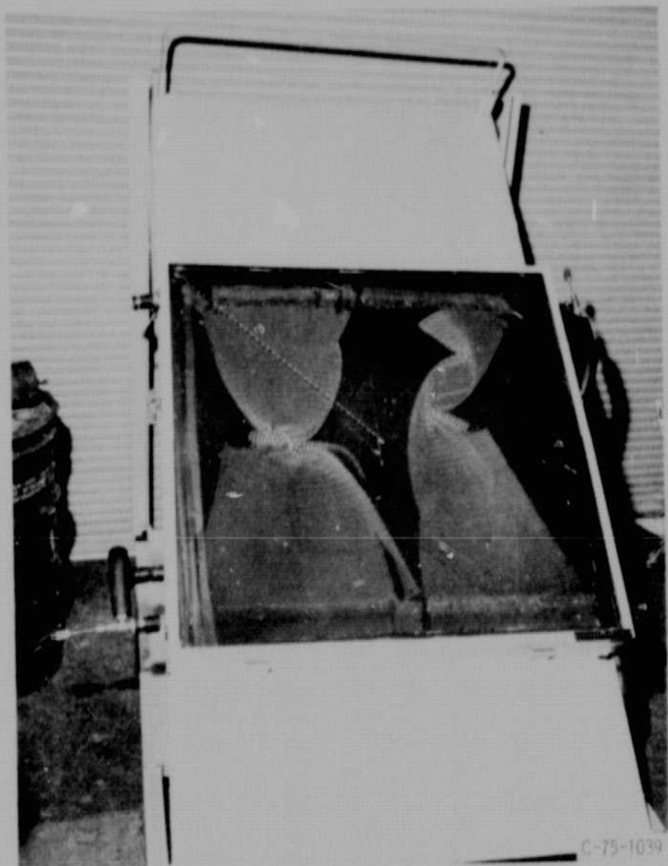

Figure 5. - Mylar honeycomb after dry operation.

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