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**AN ANALYTICAL COMPARISON OF THE EFFICIENCY OF SOLAR  
THERMAL COLLECTOR ARRAYS WITH AND WITHOUT EXTERNAL  
MANIFOLD**

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**Solar Energy**

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## TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
	LIST OF SYMBOLS	iv
	LIST OF FIGURES	vi
1.0	PURPOSE	1
2.0	SUMMARY	1
3.0	INTRODUCTION	1
4.0	DISCUSSION	2
	4.1 Internal/External Manifolds-Definition	2
	4.2 Scope of the Present Study	2
	4.3 Underlying Assumptions of Analysis	4
	4.4 Required Input Data	5
	4.5 Governing Equations	7
5.0	EXAMPLE COMPUTATION	10
6.0	RESULTS	11
7.0	CONCLUSIONS	12

APPENDIX A - LIST OF COLLECTORS IN PHASE II OF THE DOE COLLECTOR TEST PROGRAM HAVING (INTERNAL) INTEGRAL MANIFOLDS

APPENDIX B - SAMPLE PROGRAM INPUT/OUTPUT AND COMPUTER LISTING FOR COLLECTOR MANIFOLD STUDY

## LIST OF SYMBOLS

<u>Symbol</u> English:	<u>Definition</u>	<u>Units</u>
$A^*$	Collector efficiency parameter	—
$A_g$	Gross area of a single collector	ft <sup>2</sup>
$A_{gEM}$	Gross area of a single collector including effective area of related external manifold	ft <sup>2</sup>
$A_p$	Area of manifold tube (or pipe) between adjacent collector parts, $\pi DL$	ft <sup>2</sup>
$B^*$	Collector efficiency parameter	$\frac{BTU}{ft^2 \cdot hr \cdot ^\circ F}$
$\bar{c}_p$	Mean value of flow media specific heat	$\frac{BTU}{lbm \cdot ^\circ F}$
$D$	Manifold tube (or pipe) outside diameter, not including insulation	ft
$I_t$	Total insolation in plane of collector	$\frac{BTU}{ft^2 \cdot hr}$
$K_{\alpha\tau}$	Incident angle modifier parameter obtained from ASHRAE 93-77 test method	—
$L$	Nominal length of manifold between adjacent collector inlet (or outlet) ports	ft
$\dot{m}$	Rate of flow of heat transfer fluid	lbm/hr
$n$	Number of collectors placed in parallel in collector array bank	—
$Q$	Heat loss (or gain)	BTU/hr
$R$	Overall effective thermal resistance of manifold insulation covering	$\frac{ft^2 \cdot hr \cdot ^\circ F}{BTU}$
$t$	Temperature	$^\circ F$

\*A and B denote the first order collector efficiency parameters, respectively intercept and negative of slope, as determined from an ASHRAE 93-77 test.

## LIST OF SYMBOLS (cont'd)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
<b>Greek:</b>		
$\alpha$	Solar absorptivity of collector absorber plate	
$\eta_g$	Efficiency of solar collector based on gross area (not including related area of external manifold)	
$\tau$	Solar transmissivity of collector glazing	
<b>Subscripts:**</b>		
a	Referenced to ambient conditions	
B	Before mixing at an outlet manifold terminus	
C	Collector	
EM	External Manifold	
g	Referenced to gross area	
I	Inlet conditions	
j	Index (e.g., j=1 refers to first collector in array)	
L	Losses	
M	Manifold and mixed	
O	Outlet conditions	
U	Useful (e.g., $Q_U$ is the useful energy output)	

\*\*Example of subscripts:  $t_{MI,j=1}$  denotes the manifold (M) inlet (I) temperature (t) for collector number one (j=1).  $t_{MOM,j=2}$  denotes the manifold (M) outlet (O) temperature (t) for mixed (M) flow just downstream of the outlet of collector number two (j=2).

## LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	Typical Flat Plate Solar Thermal Collector With External Manifold Required	3
2	Flat Plate Solar Thermal Collector With Internal (Integral) Manifold/Header	3
3	Typical Collector Array Bank With External Manifold	6
4	Thermal Performance Curves With and Without External Manifolds -- Grumman Collector, Model 332A	13
5	Thermal Performance Curves With and Without External Manifolds -- General Electric Collector, Model TC 100	14

## **1.0 PURPOSE**

The purpose of this document is to present the results of an analytical determination of the effect of heat loss from solar thermal collector array manifolding on array thermal performance. The analysis computer program permits a direct comparison of array thermal performance with and without external manifolding.

## **2.0 SUMMARY**

A simple FORTRAN computer program was written to permit the computation of the thermal performance of solar thermal collector arrays with and without external manifolds. Computations were carried out for arrays constructed from two example solar thermal collectors (Grumman Model 332A and General Electric Model TC100) that are to be used in the DOE Solar in Federal Buildings Program. The results of the analysis are presented graphically for typical external manifold sizes and thermal insulations and are compared directly with the collector alone thermal performance (i.e., the ASHRAE 93-77 thermal performance results based on collector alone gross area).

The results indicate significant degradation in collector array thermal performance for manifold insulation having thermal resistance ( $R, \frac{\text{hr.ft}^2 \cdot \text{°F}}{\text{BTU}}$ ) values of 2.0 or less. Values of  $R$  near 7.0 and greater denote little heat loss and performance degradation. Note that the determination of an effective collector area that includes any external manifolding and spacing between adjacent collectors is critical to adequate determination of array performance. The effect of the assumed effective area on array performance is shown graphically for the two cases computed along with the effect of the various insulation  $R$  values for the external manifold.

## **3.0 INTRODUCTION**

Solar thermal collectors have been designed with a variety of inlet and outlet configurations. This is especially true in the case of flat plate and evacuated tube designs and has resulted in a variety of manifolding configurations, manifold pipe size, materials and insulations, varying quality of installation workmanship, etc.

Ideally, the system designer should minimize the amount of external manifolding required. The two most important reasons for this are as follows: 1) to reduce the physical space required for a collector array; and 2) to minimize manifold heat

losses. It is obvious that the amount of useful energy collected per unit area will be diminished if the collector array wastes space unduly and if external manifolds are poorly insulated. Thus, collectors using internal (integral) manifolds are generally preferred when designing large arrays of such collectors.

Although there are many other advantages, as well as some disadvantages, to the use of collectors having internal manifold configurations, the intent of this report is to provide a general comparison of the area and heat loss related effects of externally versus internally manifolded collectors. Section 4.0 provides an overall discussion of the study, including the basic assumptions, analytical model, and computational parameters. Section 5.0 presents two example input data sets (two collectors) and Section 6.0 presents the results of the study. General conclusions from the study are presented in Section 7.0. A list of flat plate solar thermal collectors that may qualify as having internal (integral) manifolds is presented in Appendix A. Appendix B presents both a sample computer input and output and the program listing used in the present study.

#### **4.0 DISCUSSION**

**4.1 Internal/External Manifolds-Definition.** Except for those solar collectors that use a single serpentine flow path, most flat plate solar thermal collectors have a distinct internal header/riser configuration (Figure 1). The collector of Figure 1, as configured, requires a significant external manifold for it to be connected in parallel to another collector, or collectors, in an array bank. Thus, in this report the collector of Figure 1 will be treated as having an external manifold in spite of its header/riser configuration.

The collector examples shown in Figure 2 may be considered to fit the description of internally (integrally) manifolded collectors if designed as such. Obviously, such collectors will function adequately only if the headers and connectors must be adequately sized to maintain balanced flow rates in all of the risers.

**4.2 Scope of the Present Study.** The study described in this report provides a simple, accurate comparison of the instantaneous thermal efficiencies for real and idealized flat plate solar thermal collectors with and without internal (integral) manifolds. The following parameters were varied to evaluate their effect on collector array

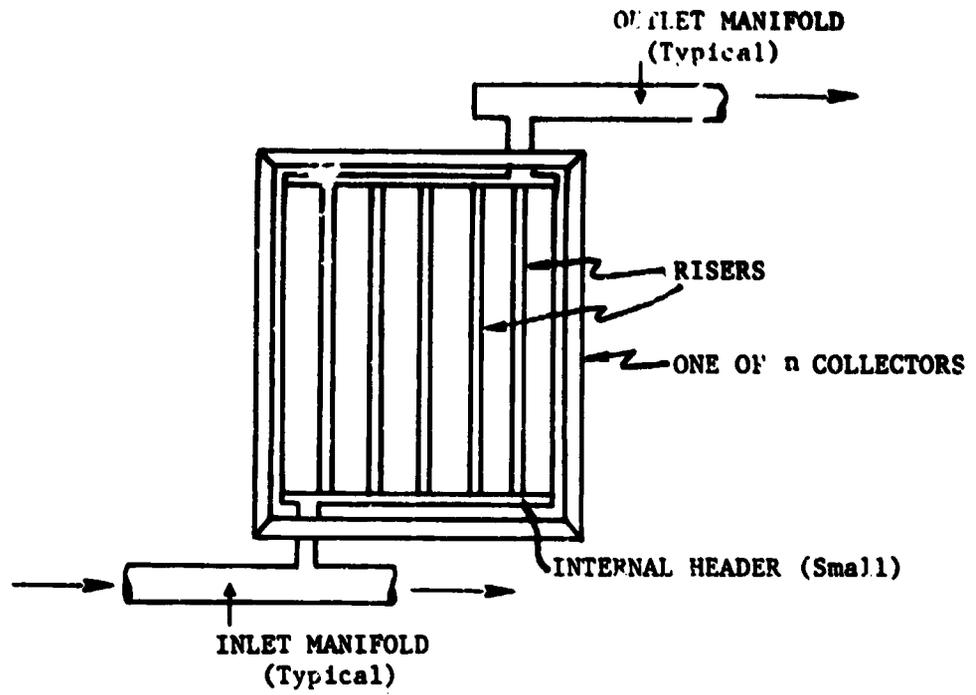


Figure 1. Typical Flat Plate Solar Thermal Collector With External Manifold Required

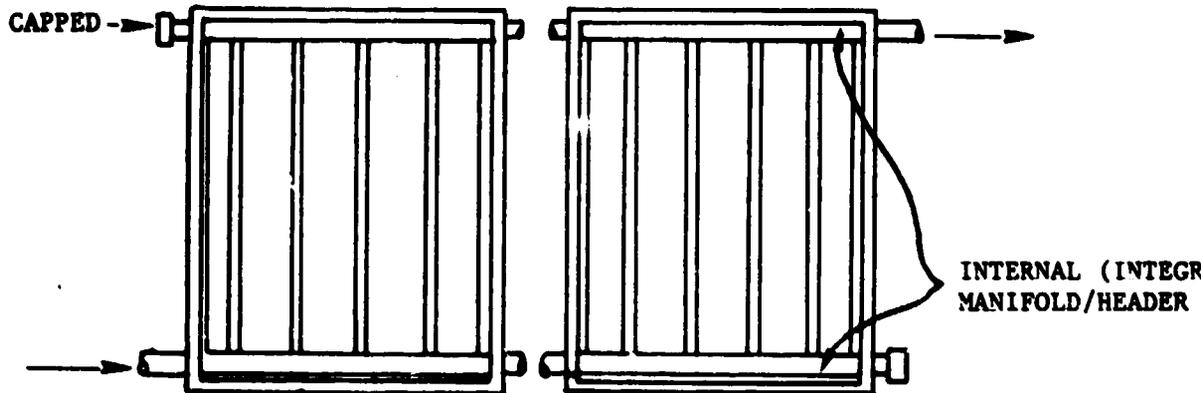


Figure 2. Flat Plate Solar Thermal Collector With Internal (Integral) Manifold/Header

efficiency:

- 1) Manifold Insulation Effective Thermal Resistance,  $R = 0.75^*$ , 2 and  $7 \frac{\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{F}}{\text{BTU}}$ .
- 2) Number of Parallel Collectors in Array Bank,  $n = 8$ .
- 3) Average Ambient Temperature,  $t_a = 40^\circ\text{F}$ .
- 4) Manifold Inlet Temperature to Array Bank,  $t_{\text{MI}} = 40.1^\circ\text{F}$ ,  $150^\circ\text{F}$ , and  $220^\circ\text{F}$ .

4.3 Underlying Assumptions of Analysis. A set of assumptions was established to provide a simple, but realistically accurate analysis. It is deemed that no single assumption seriously limits the results of the current analysis:

- 1) All collectors in an array bank shall be identical and shall use a liquid as the flow media.
- 2) The liquid flow rate through each collector shall be identical and equal to  $\dot{m}_c$ .
- 3) External manifolds—when used—shall be of a constant diameter tube (or pipe) and be uniformly insulated.
- 4) Manifold heat losses ( $Q_{\text{LM}}$ ) shall be determined from the input values of the effective insulation resistance ( $R$ ) and the difference in the calculated mean fluid temperature,  $\bar{t}_M$ , between collector inlet (or outlet) ports and the ambient temperature,  $t_a$ , i.e.,

$$Q_{\text{LM}} = \frac{A_p}{R} (\bar{t}_M - t_a) \quad (1)$$

and where  $A_p$  is the total tube (or pipe) area between collector ports on the same manifold.

- 5) The external manifolds receive no heat input from exposure to the sunlight.

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\* An R value of  $0.75 \frac{\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{F}}{\text{BTU}}$  approximates that of an uninsulated pipe.

- 6) The number of collectors,  $n$ , in an array bank shall be 10 or less for computation purposes.
- 7) The gross area of the collector array bank shall be defined as  $n$  times the effective gross area of a single collector. Two separate collector areas shall be input: a)  $A_g$  - the gross area of a single collector as defined by ASHRAE 93-77, and b)  $A_{gEM}$  - the effective gross area of a collector including its externally configured manifold. These two areas,  $A_g$  and  $A_{gEM}$ , are further defined in Figure 3.

**4.4 Required Input Data.** The following input data is required to perform the analysis for determining the effect of manifold heat losses and/or effective array size on collector array bank performance:

- 1) Collector efficiency parameters based on gross area ( $A_g$ ) and first order curve fit in accordance with ASHRAE 93-77 test results ( $A$ ,  $B$ , and  $K_{\alpha\tau}$ )

$$\eta_g = AK_{\alpha\tau} + B (t_i - t_a)/I_t \quad (2)$$

where  $B$  is defined in English units,  $K_{\alpha\tau}$  is the incident angle modifier,  $t_i$  is the collector inlet (fluid) temperature, and  $t_a$  and  $I_t$  are defined below.

- 2) Ambient temperature,  $t_a$  ( $^{\circ}\text{F}$ )
- 3) Manifold inlet temperature,  $t_{MI}$  ( $^{\circ}\text{F}$ )
- 4) Total insolation measured in the plane of the collector,  $I_t$  ( $\frac{\text{BTU}}{\text{hr}\cdot\text{ft}^2}$ )
- 5) Collector gross area,  $A_g$  ( $\text{ft}^2$ )
- 6) Collector effective gross area including external manifold,  $A_{gEM}$  ( $\text{ft}^2$ )
- 7) Flow rate through each collector,  $\dot{m}_c$  ( $\text{lbm/hr}$ )
- 8) Mean value of flow media specific heat,  $\bar{c}_p$  ( $\text{BTU/lbm}\cdot^{\circ}\text{F}$ )
- 9) Number of collectors in array bank,  $n$
- 10) Effective external area of manifold tube (pipe) between adjacent inlet (or outlet) ports,  $A_p$  ( $\text{ft}^2$ )



- 11) Effective thermal resistance of the manifold insulation,  $R$  (hr.ft<sup>2</sup>.°F/BTU). Note that the area,  $A_p$ , used in Equation (1) must correspond to the proper area as designated by the pipe insulation manufacturer. In this report the manifold pipe (tube) diameter is used in calculating the heat loss area.

4.5 Governing Equations. For simplicity in the current analysis, only linear equations and mean values of individual parameters have been utilized. Thus, the analysis proceeds with the following equations and in the general order presented.

4.5.1 Inlet Temperature for Inlet Manifold and Individual Collectors: Given the temperature,  $t_{MI}$  of the flow at the start of the inlet manifold, the heat loss from each length of inlet manifold must be computed. With the assumption that the temperature change of the fluid in the manifold is linearly related to the manifold area, ambient temperature, and insulation thermal resistance, then the temperature at the terminus of a manifold length may be computed as follows:

$$t_{MI,j} = \frac{t_{MI,j-1} \left[ (2 \dot{m}_{MI,j}) (\bar{c}_p) - \left( \frac{A_p}{R} \right) \right] + \frac{2 A_p t_a}{R}}{(2 \dot{m}_{MI,j}) (\bar{c}_p) + \left( \frac{A_p}{R} \right)} \quad (3)$$

Equation (3) is derived from an energy balance on a length of manifold, i.e.,

$$Q_{LMI,j} = \frac{A_p}{R} (t_{MI,j} - t_a) \quad (4)$$

and

$$Q_{LMI,j} = \dot{m}_{MI} \bar{c}_p (t_{MI,j-1} - t_{MI,j}) \quad (5)$$

with the mean manifold fluid temperature defined as

$$\bar{t}_{MI,j} = (t_{MI,j-1} + t_{MI,j})/2.0 \quad (6)$$

By defining  $t_{MI,j-1} = t_{MI}$  the temperature at the terminus of each inlet manifold section may be determined by repeated application of Equation (3). Further, the inlet temperature of each collector,  $t_{CI,j}$  is assumed to be equivalent to the terminus of each section of inlet manifold, i.e.,

$$t_{CI,j} = t_{MI,j} \quad (7)$$

**4.5.2 Collector Efficiency and Collector Outlet Temperature.** The outlet temperature of each collector must be determined to provide a boundary condition for the outlet manifold heat loss calculations. To accomplish this, the efficiency of each collector is computed from Equation (2) as follows:

$$\eta_{g,j} = AK_{\alpha\tau} + B(t_{CL,j} - t_a)/I_t \quad (2)$$

Then, the collector outlet temperature is computed as follows:

$$t_{CO,j} = t_{CL,j} + \frac{\eta_{g,j} I_t A_g}{\dot{m}_c c_p} \quad (8)$$

since

$$\eta_{g,j} = \frac{\dot{m}_c c_p (t_{CO,j} - t_{CL,j})}{I_t A_g} \quad (9)$$

**4.5.3 Manifold Heat Losses:** The equation for the manifold heat loss was introduced previously as

$$Q_{LM} = \frac{A_p}{R} (\bar{t}_M - t_a) \quad (1)$$

Equation (1) is written with the assumption that the mean value of the manifold flow media temperature,  $\bar{t}_M$ , may be computed by averaging the temperature at the beginning and terminus of the manifold section between adjacent collectors. With the appropriate subscripts,  $Q_{LM}$  may be formulated for both the inlet and outlet manifold sections.

Thus, for the array bank of Figure 3, the mean temperature of the flow media in the inlet manifold between collector no. 1 and collector no. 2 may be computed as

$$\bar{t}_{ML,j=2} = (t_{ML,j=1} + t_{ML,j=2})/2.0 = (t_{CL,j=1} + t_{CL,j=2})/2.0 \quad (10)$$

and so on for each inlet manifold length.

Similar computations may be made for determining the mean temperatures,  $\bar{t}_{MO,j}$  in the outlet manifold with the exception that mixing must occur in the flow between the collector outlet ports and the corresponding outlet manifold location. Thus, the mixed flow media temperature downstream of the outlet port of collector no. 2 may be computed as follows

$$t_{MOM,j=2} = \frac{(t_{MOB,j=1} \chi \dot{m}_{MO,j=1}) + (t_{CO,j=2} \chi \dot{m}_c)}{\dot{m}_{MO,j=1} + \dot{m}_c} \quad (11)$$

and so on for each point at which mixing occurs. The temperature of the flow media at the terminus of each section of the outlet manifold may be computed through the application of Equation (3) with the appropriate assignment of subscripts, i.e.,

$$t_{MOB,j} = \frac{t_{MOM,j} \left[ (2\dot{m}_{MO,j} \chi \bar{c}_p) - \left( \frac{A_p}{R} \right) \right] + \frac{2A_p t_a}{R}}{(2\dot{m}_{MO,j} \chi \bar{c}_p) + \frac{A_p}{R}} \quad (12)$$

**4.5.4 Collector Array Bank Efficiency:** After calculation of the temperature at the terminus of the outlet manifold,  $t_{MO}$ , the collector array bank efficiency and useful energy output may be computed from the following equations:

$$Q_U = n \dot{m}_c \bar{c}_p (t_{MO} - t_{MI}) \quad (13)$$

and

$$\eta_g = Q_U / (I_t A_g n) \quad (14)$$

The choice of the gross area,  $A_g$ , to use in these computations depends on the effective area for each collector with consideration given to the added area due to the external manifold. Thus, the use of Equations 13 and 14 and the appropriate effective area permits a comparison to be made with the same array bank, when using only the gross area,  $A_g$ , of the collector alone.

## 5.0 EXAMPLE COMPUTATION

Two commercially available collectors were selected as examples for this analysis. The input data was generated from their individual ASHRAE 93-77 thermal performance results and from other assumed parameters listed below:

<u>Input Parameter</u>	<u>Definition</u>	<u>Input Parameter Value for Each Collector</u>	
		<u>Grumman</u>	<u>General Electric</u>
<b>Model No.</b>	<b>Manufacturer's designation</b>	<b>332A</b>	<b>TC 100</b>
<b>A</b>	<b>Collector efficiency parameter</b>	<b>0.730</b>	<b>0.432</b>
<b>B</b>	<b>Collector efficiency parameter</b>	<b>0.844</b>	<b>0.078</b>
<b><math>K_{\alpha\tau}</math></b>	<b>Incident angle modifier</b>	<b>1.0</b>	<b>1.0</b>
<b><math>t_a</math></b>	<b>Ambient temperature</b>	<b>40°F</b>	<b>40°F</b>
<b><math>t_{MI}</math></b>	<b>Manifold inlet temperature</b>	<b>(40.1,150,220)°F</b>	<b>(40.1,150,220)°F</b>
<b><math>I_t</math></b>	<b>Total insolation</b>	<b>310 <math>\frac{BTU}{hr.ft^2}</math></b>	<b>310 <math>\frac{BTU}{hr.ft^2}</math></b>
<b><math>A_g</math></b>	<b>Gross area of a single collector</b>	<b>31.80 ft<sup>2</sup></b>	<b>17.41 ft<sup>2</sup></b>
<b><math>A_{gEM}</math></b>	<b>Gross area of a single collector including related external manifolds</b>	<b>35.55 ft<sup>2</sup></b>	<b>19.10 ft<sup>2</sup></b>
<b><math>\dot{m}_c</math></b>	<b>Collector fluid flow rate</b>	<b>400 lbm/hr</b>	<b>110 lbm/hr</b>
<b><math>\bar{c}_p</math></b>	<b>Mean specific heat of flow</b>	<b>1.0 <math>\frac{BTU}{lbm.°F}</math></b>	<b>1 <math>\frac{BTU}{lbm.°F}</math></b>
<b>n</b>	<b>Number of collectors in array bank</b>	<b>8</b>	<b>8</b>
<b><math>A_p</math></b>	<b>Area of manifold tube (pipe) between collector ports</b>	<b>2.2 ft<sup>2</sup></b>	<b>2.2 ft<sup>2</sup></b>
<b>R</b>	<b>Insulation thermal resistance of manifold covering</b>	<b>(0.75,2.0,7.0) <math>\frac{hr.ft^2.°F}{BTU}</math></b>	<b>(0.75,2.0,7.0) <math>\frac{hr.ft^2.°F}{BTU}</math></b>

The effective gross area with external manifold ( $A_{gEM}$ ) was estimated from the collector gross area ( $A_g$ ) and the added area due to the manifold and collector spacing (Figure 3).

The temperatures and total insolation were chosen to produce a typical range of thermal performance for the example collectors. The insulation thermal resistance parameter (R) was varied from essentially no insulation ( $R = 0.75 \frac{\text{hr}\cdot\text{ft}^2\cdot\text{O}^\circ\text{F}}{\text{BTU}}$ ) to a relatively high degree of insulation ( $R = 7.0 \frac{\text{hr}\cdot\text{ft}^2\cdot\text{O}^\circ\text{F}}{\text{BTU}}$ ) for external manifolds.

## 6.0 RESULTS

The manifold heat loss analysis was applied to two separate collectors (Grumman Model 332A and General Electric Model TC100) as described in the example computation (Section 5.0). The results of the computations are shown in Figures 4 and 5 for the Grumman and General Electric collectors, respectively.

The curves labeled  $\eta_g$  in both Figures 4 and 5 represent the ASHRAE 93-77 thermal performance of the collectors based on the collector's gross area ( $A_g$ ). The curves labeled  $\eta_{gEM}$  are representative of the ASHRAE 93-77 thermal performance modified by the effective gross area ( $A_{gEM}$ ) of the collector including the external manifolds. Note that the value of the effective gross area must be carefully specified, since it is indicative of the gross "array" area used to produce useful collected energy.

Associated with each curve labeled  $\eta_{gEM}$  are thermal performance curves illustrating the effects of various pipe insulations. Values of the insulation thermal resistance (R) and the associated manifold area ( $A_p$ ) between adjacent collectors are input to the computer program. Figures 4 and 5 show the effect on array efficiency with R values of 0.75 (essentially a bare pipe), 2.0, and  $7.0 \frac{\text{ft}^2\cdot\text{hr}\cdot\text{O}^\circ\text{F}}{\text{BTU}}$ . Thus, the computer analysis permits optimization of the pipe insulation type and its effective thermal resistance.

Note that the computer printout (see Appendix B) includes all of the inlet and outlet temperatures, manifold heat losses, and efficiencies of each individual collector. Also, the printout includes the array inlet and outlet temperatures, the useful energy delivered from the array and the array efficiency. Thus, manifold heat losses can be readily evaluated and plotted to indicate the energy lost by the array.

## **7.0 CONCLUSIONS**

The computer analysis presented in this report permits an evaluation of the effect of various manifold insulations on solar thermal collector array efficiency. The analysis is simple and produces results quickly. It is believed that the assumptions made to develop the analysis aren't serious limitations to the method. The computer code can be easily modified. For example, the modification to the code to calculate the mean value of the flow media specific heat as a function of temperature may be readily accomplished.

The results indicate significant degradation in collector array thermal performance for manifold insulation having thermal resistance values of  $R = 2.0 \text{ hr.ft}^2 \cdot ^\circ\text{F}/\text{BTU}$  or less. Values of  $R$  near 7.0 and greater results in little heat loss and performance degradation.

Note that the determination of an effective collector area that includes any external manifolding and spacing between adjacent collectors is critical to adequate determination of array performance. The effect of the assumed effective gross area for the two example cases in this report show a dramatic effect on array efficiency.

GRUMMAN COLLECTOR  
 MODEL NO. 332 A  
 (SINGLE-GLAZED, FLAT PLATE)  
 8 COLLECTOR BANK

$$\text{THERMAL RESISTANCE, } R \left( \frac{\text{h} \cdot \text{ft}^2 \cdot \text{°F}}{\text{Btu}} \right)$$

0.75 2.0 7.0

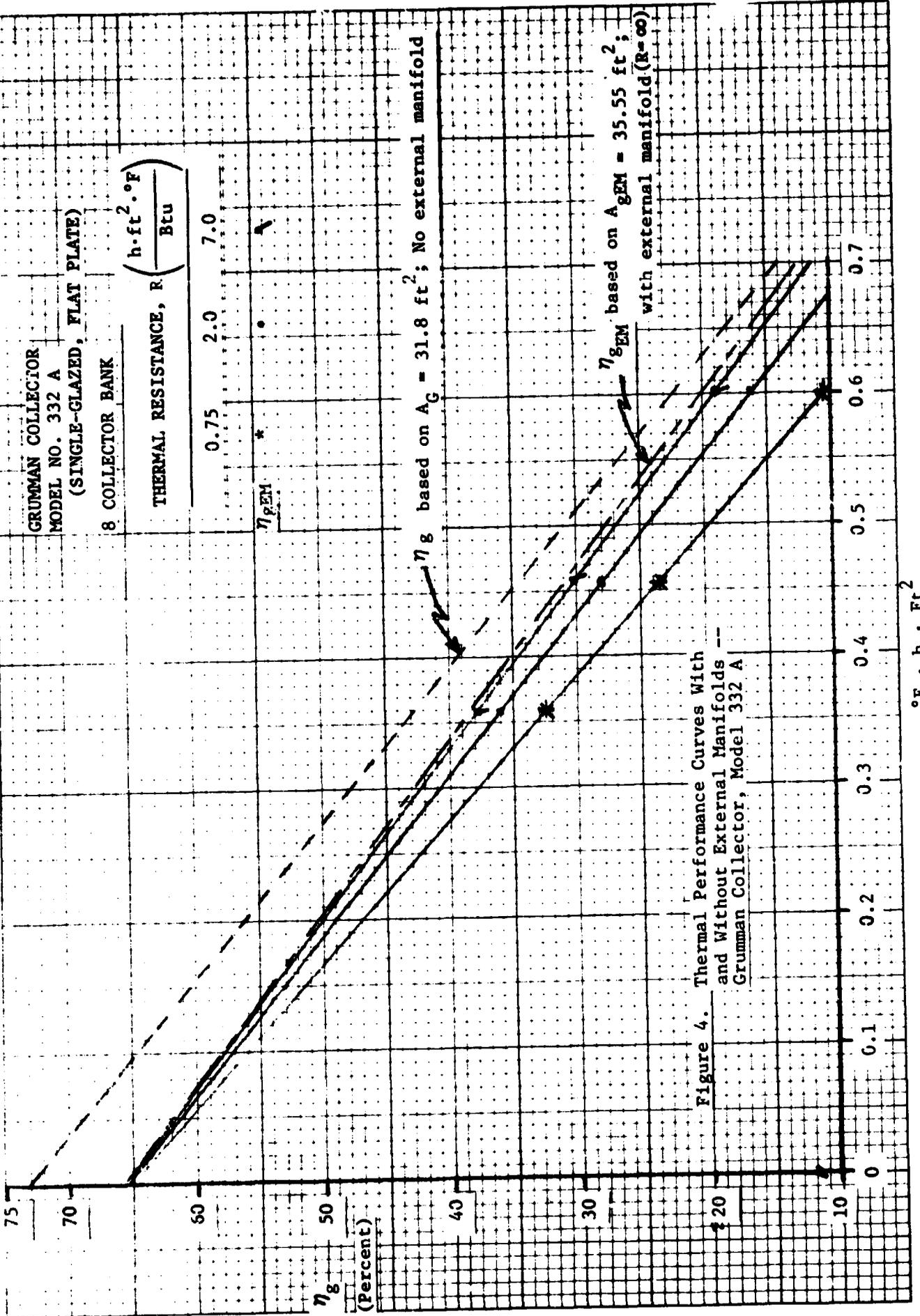
$\eta_{PEM}$

$\eta_g$   
 (Percent)

$\eta_g$  based on  $A_G = 31.8 \text{ ft}^2$ ; No external manifold

$\eta_{gEM}$  based on  $A_{gEM} = 35.55 \text{ ft}^2$ ; with external manifold ( $R = \infty$ )

Figure 4. Thermal Performance Curves With and Without External Manifolds -- Grumman Collector, Model 332 A



$$(t_i - t_a) / I_t, \frac{\text{°F} \cdot \text{h} \cdot \text{Ft}^2}{\text{Btu}}$$

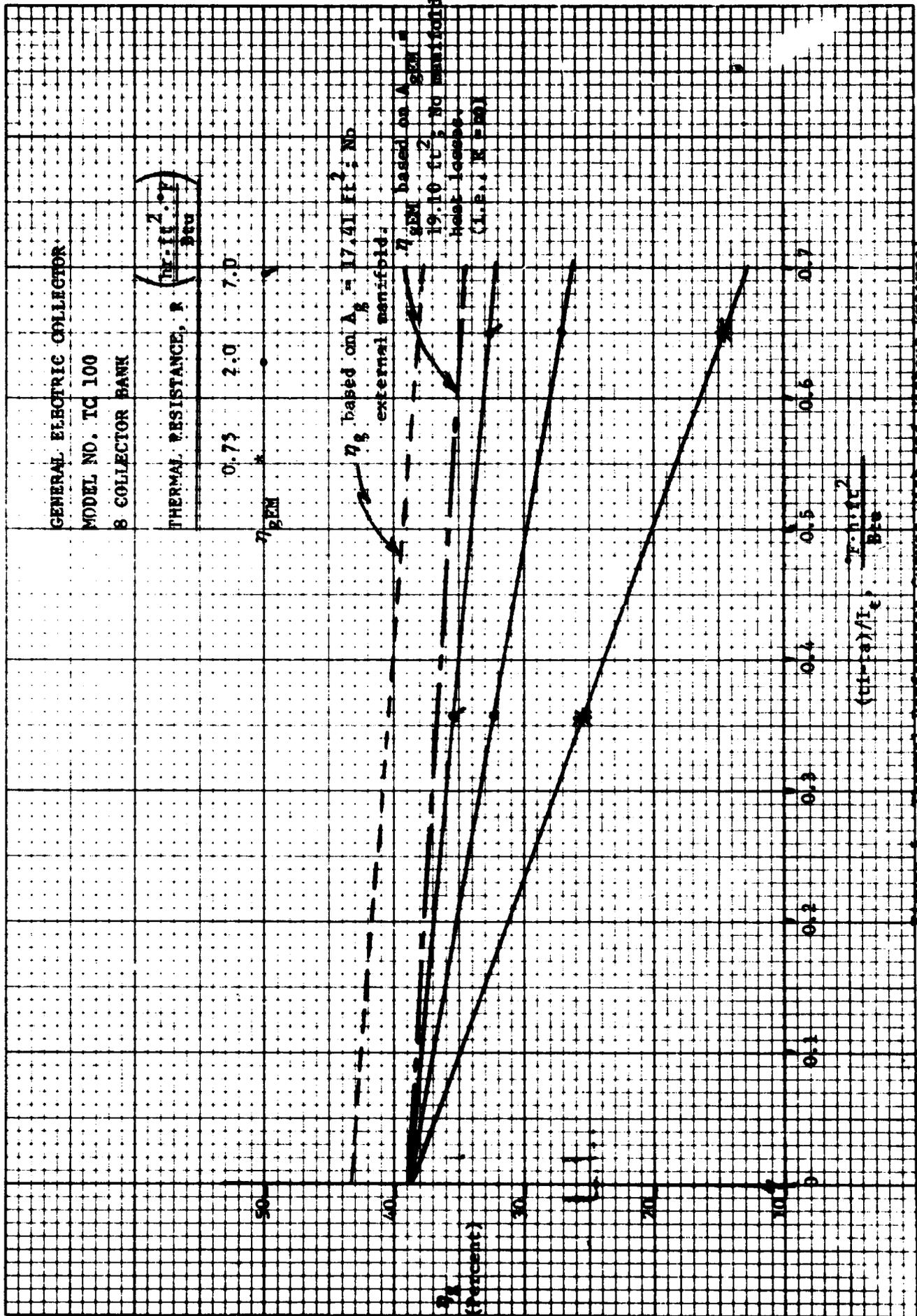


Figure 5. Thermal performance curves with and without external manifolds--General Electric Collector, Model TC 100

**APPENDIX A**

**LIST OF COLLECTORS IN PHASE I OF THE  
DOE COLLECTOR TEST PROGRAM HAVING  
(INTERNAL) INTEGRAL MANIFOLDS**

## APPENDIX A (cont'd)

A cursory review of the collectors tested in Phase I of the DOE Collector Test Program indicate that the list of collectors below have (internal) integral manifolds. The list cannot be considered fully complete or accurate for the following reasons:

- 1) Approximately 20 sets of collector drawings and/or specifications were not available for review.
- 2) No evaluation was made of the flow capacity of the individual collector integral manifold, i.e., the number of collectors of a particular model that could be placed in parallel without an external manifold was not determined.

Approximately 100 sets of collector drawings were reviewed to identify the following 19 collectors believed to fall in the category of internal manifolds.

### LIST OF COLLECTORS IN PHASE I OF THE DOE COLLECTOR TEST PROGRAM HAVING INTEGRAL (INTERNAL) MANIFOLDS

<u>NAME</u>	<u>MODEL</u>
Daystar Corporation	21-B, 21-C
Energy Systems, Inc.	1111D, 1211S
Federal Energy Corporation	F-200
Gulf Thermal Corporation	CU30-SL
International Technology/Solar Corporation	Mark III (4'), Mark V (3')
Oahu Solar Products	Solapak 150
PPG Industries, Inc.	C-524
Precision Industries, Inc.	50-11-3MG
Solar Energy Products, Inc.	CU-30-WW
Solar Enterprises, Inc.	SLIMLINER
Solar USA	28S, 37S
Solaron of North America, Inc.	SCO-200
Specialty Mfg. Co. (Insulator)	SA120-125SS
Sun Life Solar Products	SP-100
Sun Power Systems, Ltd.	C38B-H
Sunearth Solar Products Corporation	3597ADGFB
Sunworks Division of Enthorpe, Inc.	N/A
Wallace Company	Wallace Company Solar Collector
Wilcox Manufacturing Corporation	SC8000

**APPENDIX B**

**SAMPLE PROGRAM INPUT/OUTPUT AND  
COMPUTER LISTING FOR COLLECTOR MANIFOLD STUDY**

APPENDIX B (cont'd)

SAMPLE PROGRAM INPUT/OUTPUT  
GRUMMAN COLLECTOR, MODEL 332A

COLLECTOR MANIFOLD STUDY

INTERCEPT EFFICIENCY=0.730 SLOPE=0.844

INCIDENT ANGLE MODIFIER VALUES FOR 0, 10, 20, ... 90 DEGREES ARE

1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000

AMBIENT TEMPERATURE= 40.0 MANIFOLD INLET TEMPERATURE=220.0 TOTAL FLUX=300.0

COLLECTOR GROSS AREA=31.80 COLLECTOR GROSS AREA WITH E-M=35.55

COLLECTOR MASS FLOW RATE=400.00 FLUID SPECIFIC HEAT=1.000

NUMBER OF COLLECTORS= 8 MANIFOLD PIPE AREA(S)= 2.2 MANIFOLD R VALUE= 2

COLLECTOR NO. = 1 TCI=219.9 TCO=225.3 TMI=219.9 TMOP=225.3 TMOB=224.8

TBM1=220.0 TBM0=225.0 QLM1=198.0 QLM0=203.5

MDOTMI=3200. MDOTMO= 400. NG=0.224

COLLECTOR NO. = 2 TCI=219.9 TCO=225.2 TMI=219.5 TMOP=225.0 TMOB=224.7

TBM1=219.9 TBM0=224.9 QLM1=197.9 QLM0=203.3

MDOTMI=2668. MDOTMO= 800. NG=0.224

COLLECTOR NO. = 3 TCI=219.8 TCO=225.1 TMI=219.8 TMOP=224.9 TMOB=224.7

TBM1=219.8 TBM0=224.8 QLM1=197.8 QLM0=203.3

MDOTMI=2400. MDOTMO=1200. NG=0.224

COLLECTOR NO. = 4 TCI=219.7 TCO=225.0 TMI=219.7 TMOP=224.8 TMOB=224.7

TBM1=219.7 TBM0=224.7 QLM1=197.7 QLM0=203.2

MDOTMI=2000. MDOTMO=1600. NG=0.224

COLLECTOR NO. = 5 TCI=219.6 TCO=224.9 TMI=219.6 TMOP=224.7 TMOB=224.6

TBM1=219.6 TBM0=224.7 QLM1=197.6 QLM0=203.1

MDOTMI=1600. MDOTMO=2000. NG=0.225

COLLECTOR NO. = 6 TCI=219.4 TCO=224.8 TMI=219.4 TMOP=224.6 TMOB=224.6

TBM1=219.5 TBM0=224.6 QLM1=197.4 QLM0=203.1

MDOTMI=1200. MDOTMO=2400. NG=0.225

COLLECTOR NO. = 7 TCI=219.2 TCO=224.5 TMI=219.2 TMOP=224.5 TMOB=224.5

TBM1=219.3 TBM0=224.5 QLM1=197.2 QLM0=203.0

MDOTMI= 800. MDOTMO=2800. NG=0.226

COLLECTOR NO. = 8 TCI=218.7 TCO=224.1 TMI=218.7 TMOP=224.4 TMOB=224.4

TBM1=218.9 TBM0=224.4 QLM1=196.8 QLM0=202.8

MDOTMI= 400. MDOTMO=3200. NG=0.227

COLLECTOR ARRAY PERFORMANCE

TMI= 220.00 TMO = 224.36

QLEM= 13965. NEMAG=0.183 NEMFM=0.164

APPENDIX B (cont'd)

COMPUTER LISTING FOR COLLECTOR MANIFOLD STUDY

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DIMENSION TCI(10), TNI(10), G.M.(10), TEMT(10)
DIMENSION TCO(10), TNO(10), TMO(10), G.M.O(10), TMOB(10)
REAL MDOTHI(10), KAT(10), IT, MDOTC, NG(10),
C MDOTMO(10), NENAG, NENAM
1 CONTINUE
WRITE(7,1001)
1001 FORMAT(' TYPE IN THE NUMBER OF COLLECTORS: '$)
READ(5,*)NC
IF(NC.LE.0) GO TO 600
WRITE(7,1002)
1002 FORMAT(' TYPE IN THE INTERCEPT AND SLOPE (POS): '$)
READ(5,*)IB,B
WRITE(7,1003)
1003 FORMAT(' TYPE IN THE E-W INCIDENT ANGLE MODIFIER '$)
WRITE(7,1004)
1004 FORMAT(' FOR 0, 20, 28, ... 90 DEGREES: '$)
READ(5,*)KAT
WRITE(7,1005)
1005 FORMAT(' TYPE IN THE AMBIENT TEMPERATURES: '$)
READ(5,*)TA
WRITE(7,1006)
1006 FORMAT(' TYPE IN THE TEMPERATURE AT THE '$)
WRITE(7,1007)
1007 FORMAT(' MANIFOLD INLET: '$)
READ(5,*)TMI
WRITE(7,1008)
1008 FORMAT(' TYPE IN THE INSOLATION VALUE: '$)
READ(5,*)IT
WRITE(7,1009)
1009 FORMAT(' TYPE IN THE COLLECTOR GROSS AREA: '$)
READ(5,*)AG
WRITE(7,1010)
1010 FORMAT(' TYPE IN THE GROSS AREA WITH EXTERNAL MANIFOLD: '$)
READ(5,*)AGEM
WRITE(7,1011)
1011 FORMAT(' TYPE IN THE COLLECTOR FLOW RATE: '$)
READ(5,*)MDOTC
WRITE(7,1012)
1012 FORMAT(' TYPE IN THE SPECIFIC HEAT: '$)
READ(5,*)CP
WRITE(7,1013)
1013 FORMAT(' TYPE IN THE AREA OF THE MANIFOLD PIPE: PTDL: '$)
READ(5,*)AP
WRITE(7,1014)

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1014 FORMAT(' TYPE IN THE MANIFOLD R VALUE: ')
      READ(5,*)R
      WRITE(6,2001)
2001 FORMAT(1X,'COLLECTOR MANIFOLD STUDY')
      WRITE(6,2002)A,B
2002 FORMAT(1X,'INTERCEPT EFFICIENCY=',F5.3,5X,
C 'SLOPE=',F5.3)

      WRITE(6,2003)KAT
2003 FORMAT(1X,'INCIDENT ANGLE MODIFIER VALUES FOR
C B, 10, 20, ... 90 DEGREES ARE',/1X,10F7.3)
      WRITE(6,2004)TA, THII, TI
2004 FORMAT(1X,'AMBIENT TEMPERATURE=',F5.1,3X,
C 'MANIFOLD INLET TEMPERATURE=',F5.1,3X,
C 'TOTAL FLUX=',F5.1)
      WRITE(6,2005)AG, AGEN
2005 FORMAT(1X,'COLLECTOR GROSS AREA=',F5.2,5X,
C 'COLLECTOR GROSS AREA WITH E-A=',F5.2)
      WRITE(6,2006)MDOTC, CP
2006 FORMAT(1X,'COLLECTOR MASS FLOW RATE=',F6.2,5X,
C 'FLUID SPECIFIC HEAT=',F5.3)
      WRITE(6,2007)NC, AP, R
2007 FORMAT(1X,'NUMBER OF COLLECTORS=',I2,5X,
C 'MANIFOLD PIPE AREA(S)=',F5.1,5X,
C 'MANIFOLD R VALUE=',F5.2)
C INITIAL CONDITIONS
MDOTHI(1)=NC*MDOTC
TCI(1)=(THII*(2.*MDOTHI(1)*CP-AP/R)
C +(2.*AP*TA)/R)/(2.*MDOTHI(1)*CP+AP/R)
THI(1)=TCI(1)
TBI(1)=(THII+TCI(1))/2
GLMI(1)=(AP/R)*(TBI(1)-TA)
DO 100 J=2,NC
MDOTHI(J)=(NC-J+1)*MDOTC
TCI(J)=(THI(J-1)*(2.*MDOTHI(J)*CP-AP/R)
C +(2.*AP*TA)/R)/(2.*MDOTHI(J)*CP+AP/R)
THI(J)=TCI(J)
TBI(J)=(THI(J-1)+TCI(J))/2
GLMI(J)=(AP/R)*(TBI(J)-TA)
100 CONTINUE
XXAT=1
DO 200 J=1,NC
NG(J)=A*XXAT-B*((TCI(J)-TA)/IT)
TCD(J)=TCI(J)+(NG(J)*IT*AG)/(MDOTC*CP)
MDOTHO(J)=J*MDOTC

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200 CONTINUE
   TMOB(1)=TCO(1)
   TMOB(1)=(TMOB(1)*(2.*MDOTMO(1)*CP+AP/R)+
C 2.*FP+TA/R)/(2.*MDOTMO(1)*CP+AP/R)
   DO 300 J=2,NC
   TMOB(J)=(TMOB(J-1)*MDOTMO(J-1)+TCO(J)*MDOTC)
C /MDOTMO(J-1)+MDOTC)
   TMOB(J)=(TMOB(J)*(2.*MDOTMO(J)*CP+AP/R)
C +2.*FP+TA/R)/(2.*MDOTMO(J)*CP+AP/R)
300 CONTINUE
   DO 400 J=1,NC
   TEMO(J)=(TMOB(J)+TMOB(J))/2
   QLMO(J)=(AP/R)*(TEMO(J)-TA)
400 CONTINUE

   TMO=TMOB(NC)
   QLEM=NC*MDOTC*CP*(TMO-TMI)
   NEMRG=QLEM/(IT+RG+NC)
   NEMRM=QLEM/(IT+RG+NC)
   DO 500 J=1,NC
   WRITE(6,3001)J,TCI(J),TCO(J),TMI(J),TMOB(J),TMOB(J)
3001 FORMAT(1X,'COLLECTOR NO =',I2,3X,'TCI=',F5.1,
C 3X,'TCO=',F5.1,3X,'TMI=',F5.1,3X,'TMOB=',F5.1,
C 3X,'TMOB=',F5.1)
   WRITE(6,3002)TEMO(J),TEMO(J),QLMO(J),QLMO(J)
3002 FORMAT(23X,'TEMO=',F5.1,3X,'TEMO=',F5.1,3X,
C 'QLMO=',F5.1,3X,'QLMO=',F5.1)
   WRITE(6,3003)MDOTMI(J),MDOTMO(J),NG(J)
3003 FORMAT(23X,'MDOTMI=',F5.0,3X,'MDOTMO=',F5.0,
C 3X,'NG=',F5.3)
500 CONTINUE
   WRITE(6,3006)
3006 FORMAT(1X,'COLLECTOR ARRAY PERFORMANCE')
   WRITE(6,3005)TMI,TMO
3005 FORMAT(23X,'TMI=',F7.2,3X,'TMO=',F7.2)
   WRITE(6,3004)QLEM,NEMRG,NEMRM
3004 FORMAT(23X,'QLEM=',F7.0,3X,'NEMRG=',
C F5.3,3X,'NEMRM=',F5.3)
   GO TO 1
600 CONTINUE
   STOP
   END

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