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Selection of Parabolic Solar Collector Field Arrays

G. W. Treadwell

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SELECTION OF PARABOLIC SOLAR COLLECTOR FIELD ARRAYS

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ABSTRACT

A technique has been developed whereby the number of columns and rows of parabolic solar collectors required to achieve a given task can be determined for steady state operational conditions.

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SELECTION OF PARABOLIC SOLAR COLLECTOR FIELD ARRAYS

Introduction

Among the numerous problems which must be addressed in the design, layout, and control of a parabolic solar collector field are the number of rows and columns of the parabolic solar collectors required to achieve a given task. There are many influencing factors, including the required liquid temperature rise, the volume flow rate, the temperature of operation, external environmental conditions, collector design, and solar tracking technique.

This particular problem has been analyzed rather thoroughly by Lee, Schimmel, and Abbin.[1] However, the analysis excluded wind losses and collector design variations. In addition, the noted work was not reduced to a set of design curves. The purpose of this study is to analyze the influence of varying solar insolation, collector design variations, and external environmental conditions, and to present the material in such a manner that selection of field arrays can be easily made as a function of differing requirements.

Analyses of Field Arrays

Limits

It is obvious that when there is no liquid flow through a solar collector field, the energy collected, or collector efficiency, is zero. One can also imagine the situation in which the liquid must be pumped through an array at such a high velocity that the pump work required due to friction losses could equal the energy absorbed by the collectors. Both situations are obviously undesirable, but they illustrate the approach taken in the present analysis, which is to select arrays that will operate within acceptable flow limits. The object is to establish flow rate limits which permit adequate energy collection and have acceptable pump losses.

In order to accomplish this, most factors which are normally considered as variable must be held as constant for the moment (e.g. wind velocity, sink temperature, receiver tube size, etc.). Furthermore, certain limits of validity must be assumed for the results to allow a more compact presentation. For example, the total hemispherical emittance of an absorber coating changes slightly with operating temperature. In this study, as will be shown, it is reasonable to assume that the results are not significantly affected by the variations in operating temperatures.

Evaluation Designs

The basic collector design selected for analysis consists of a 2.745 x 3.66 m (9 x 12 feet) parabolic reflector with a 90° rim angle.[2] The receiver tube design is shown in Figure 1. The calculated tube diameter is 1.67 inches.[2] The glass envelope annulus is approximately 0.35 in. to prevent convection losses across the unevacuated gap. This study was conducted without a vacuum in the gap.

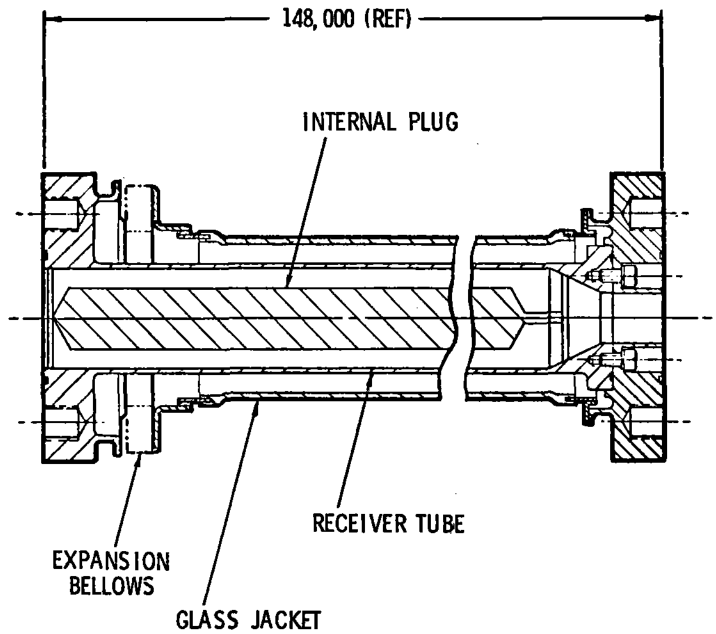


Figure 1

As a variation in the design, internal tubular plugs to force annular liquid flow within the receiver tubes are also included. Although plugs will cause lower Reynolds numbers, the change in the hydraulic diameter results in an increase in the film coefficient of heat transfer and therefore a higher collector efficiency.

The reflectance of the mirror surface is important. For this study, two values were used, $\rho = 0.68$ and $\rho = 0.78$. A measured specular reflectance, within a 10 milliradian solid angle, of Alzac* specimens is 0.68[3]; 0.78 represents the reflectance of a material yet to be defined.

The fluid used for this study is Therminol 66†, a liquid used in heat transfer applications.

---

* Alcoa

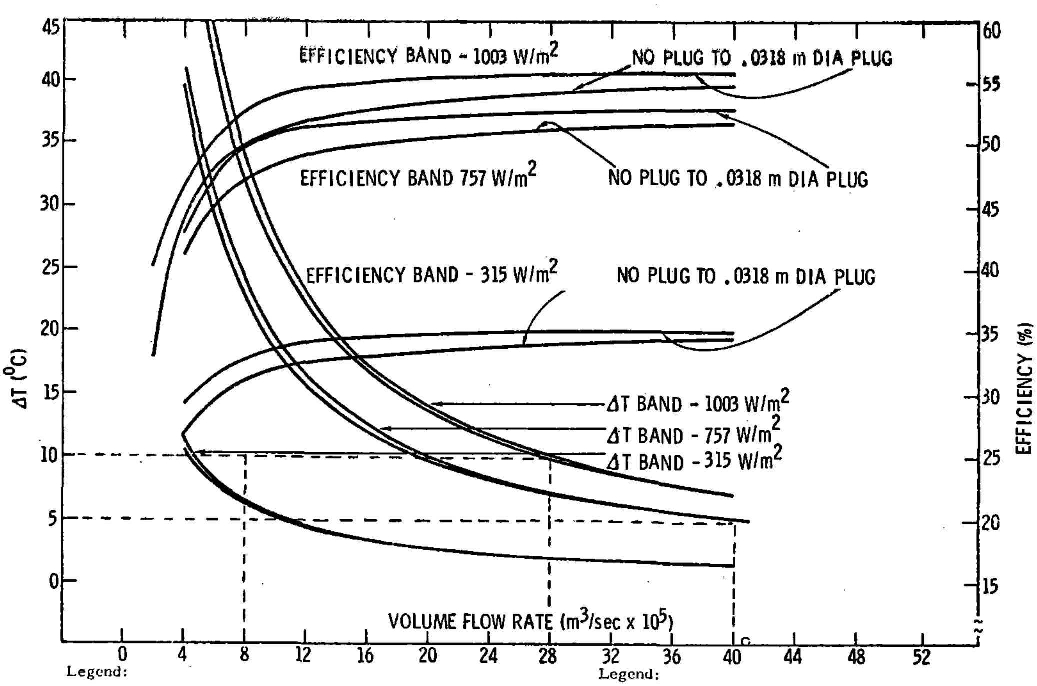
† Monsanto Industrial Chemicals Co.

Computer Code

The analysis was conducted with the use of the code developed by M. W. Edenburn.[4] The code was modified slightly (Appendix A). This code analyzes heat balances along incremental lengths of the receiver tube. In this analysis, the collector axis was always normal to the sun. As will be seen, this approach allows nonnormality to be handled through simple manual calculations and therefore allows the results to be applicable to either north-south or east-west collector orientations since the analysis considers one collector at a time.

Determination of Minimum Acceptable Flow Rate

The results of a number of computer runs for a given set of conditions as listed in the legend are portrayed on Figure 2. Inspection of Figure 2 reveals that the efficiency curves, in general, have a significant slope change in the vicinity of a volume flow rate equal to 0.00008 m^3/sec. The effect of internal plugs is to permit slower flow for the same efficiency as non-plugged receiver tubes. The efficiency relates directly to the energy absorbed in the collector fluid $\left[\text{e.g., } 1003 \frac{W}{m^2}\left(\frac{1\,J}{Wsec}\right)(2.743m)(3.658m)(50\%\text{ efficiency}) = 5032 \frac{J}{sec}\text{ energy absorbed}\right]$; therefore, it is very desirable for the volume flow rate to be such that the efficiency remains to the right of the knee in Figure 2.



Legend:
0.0429m OD receiver tube; 0.0396m I. D.
2.743m x 3.658m collector 90° rim angle
α = 0.95, ϵ = 0.3, ρ = 0.78
25°C sink temperature
2.2 m/sec wind velocity
260°C start temperature
solar input: 1003 w/m^2; 757 w/m^2; 315 w/m^2
Plugs to: .0318 m dia.

Legend:
1-11/16 OD receiver tube 1.5575" I. D.
9 x 12' collector; 90° rim angle
α = 0.95, ϵ = 0.30, ρ = 0.78
77° sink temperature
5 mph wind
500°F start temperature
solar input: 318 Btu/ft^2-hr ; 240 Btu/ft^2-hr; 100 Btu/ft^2-hr
Plugs to: 1.25 in. dia.

Figure 2

If the minimum flow rate is limited to 0.00008 m^3/sec, it is observed that a 10^oC temperature change of the liquid in the receiver tube cannot be obtained with a solar insolation of 315 $\frac{W}{m^2}$; an insolation of approximately 475 $\frac{W}{m^2}$ would be required (see intersection of dotted lines).

A collector requiring a temperature rise of 10^oC could be operated between insolation limits of 475 $\frac{W}{m^2}$ and 1003 $\frac{W}{m^2}$, with corresponding flow rates between 0.00008 $\frac{m^3}{sec}$ and 0.00028 $\frac{m^3}{sec}$.

If it is assumed that Figure 2 applies to collectors connected in series, a series of 10 non-plugged collectors, with a flow of 0.00028 $\frac{m^3}{sec}$ and solar insolation of 1003 $\frac{W}{m^2}$, can achieve a 100^oC temperature rise. At an insolation of 757 $\frac{W}{m^2}$ and a flow rate of 0.00040 $\frac{m^3}{sec}$, 20 collectors in series will achieve a 100^oC temperature rise.

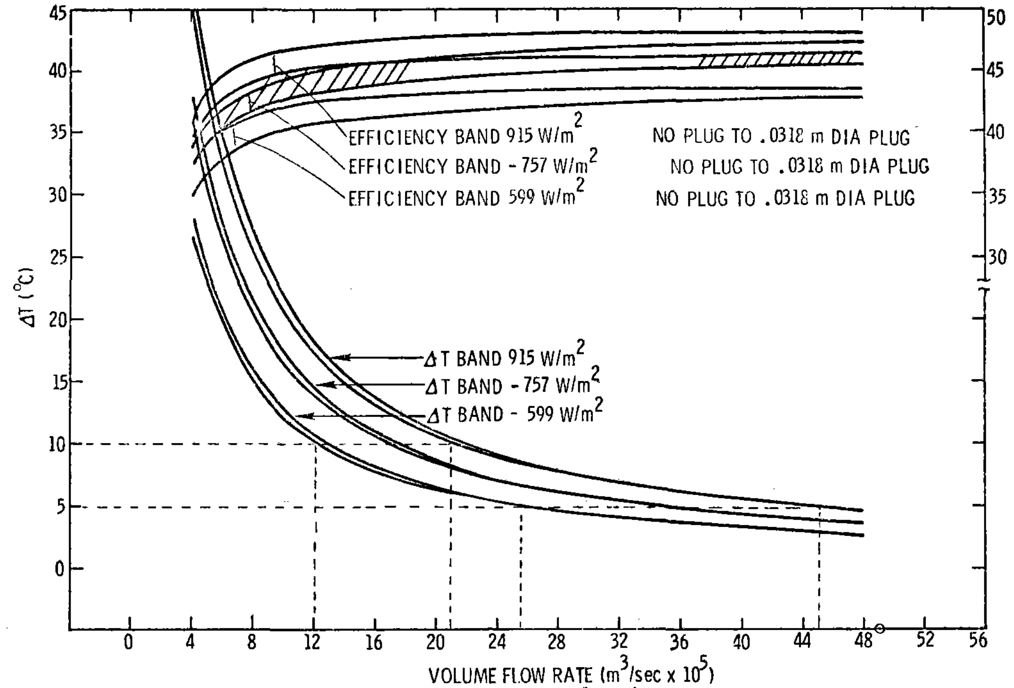
Once the required temperature rise through a string of collectors is established, inspection of Figure 2 permits determination of the number of collectors in series and the flow rate limits.

In Figure 3, the mirror reflectance has been lowered when compared to Figure 2 data. The minimum flow rate should still be 0.00008 $\frac{m^3}{sec}$. A review of Figure 3 shows that for insolations between 599 W/m^2 and 915 W/m^2, 20 collectors in series could be operated at flow rates between 0.00026 m^3/sec and 0.00045 m^3/sec and 10 collectors in series could be operated at flow rates between 0.00012 m^3/sec and 0.00022 m^3/sec to maintain a total temperature rise of 100^oC. In essence, the minimum acceptable insolation determines the lowest flow rate and options for the number of collections in series. As can be judged from Figure 3, 20 collectors in series can operate at lower insolation levels than 10 in series without going below a flow rate of 0.00008 m^3/sec.

In for foregoing examples, the data on Figures 2 and 3 have been assumed to be valid for approximately a 100^oC range. This is not an unreasonable assumption, as will be illustrated through the use of Figure 4. This figure illustrates changes in efficiencies and temperature changes due to collector operation at temperatures other than 260^oC (500^oF). Inspection of Figure 4 reveals a linearity of the ΔT curves and a slight nonlinearity in the efficiency curves. For example, at a flow rate of 0.000285 m^3/sec:

$$\left.\begin{array}{l} \Delta T\ 204^oC = 11.1^o \\ \Delta T\ 316^oC = 8.9^o \end{array}\right\} \overline{\Delta T} = 10.0^o \text{ vs } \Delta T\ 260^oC = 10.0^o$$

$$\left.\begin{array}{l} \text{Eff. } 204^oC = 59.9\% \\ \text{Eff. } 316^oC = 51.5\% \end{array}\right\} \overline{\text{Eff.}} = 55.7\% \text{ vs Eff. } 260^oC = 55.1\%$$



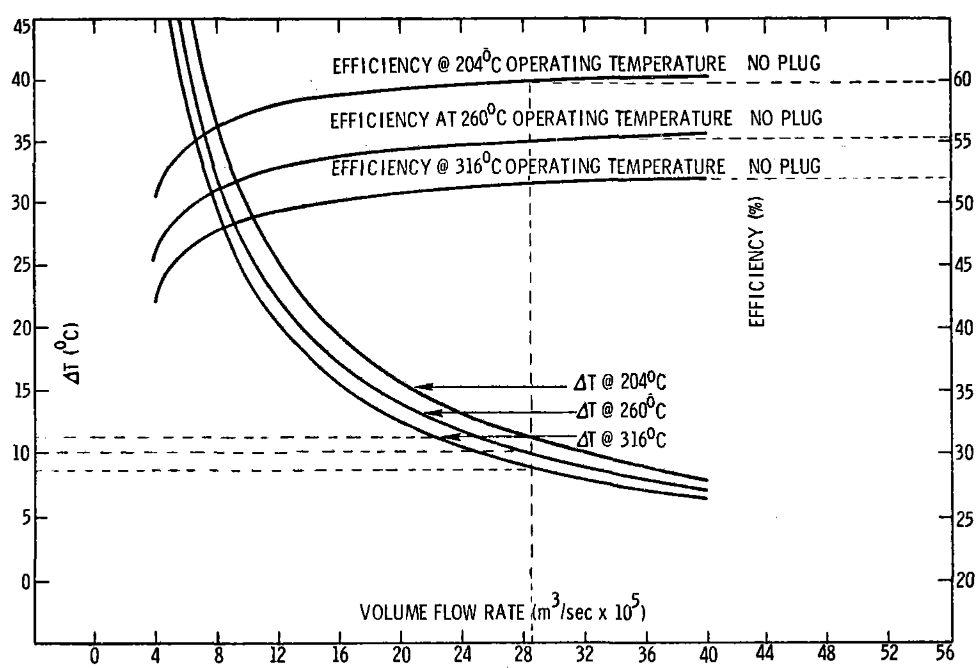
Legend:

0.0413m OD receiver tube; 0.038m I.D. unplugged
2.743m x 3.658m collector, 90° rim angle
α = 0.95 ϵ = 0.25 ρ = 0.68
25°C sink temperature
4.5 m/sec wind velocity
260°C start temperature

Legend:

1 5/8" OD receiver tube 1.495" I.D.
9' x 12' collector 90° rim angle
α = 0.95, ϵ = 0.25, ρ = 0.68
77°F sink temperature
10 mph wind
500°F start temperature
Solar Input = 290 Btu ft^2 hr; 240 Btu/ft^2-hr; 190 Btu/ft^2-hr
Plug: 1.25" dia.

Figure 3



Legend:

0.0413m OD receiver tube; 0.038m I.D. unplugged
2.743m x 3.658m reflect; 90° rim angle
α = 0.95, ϵ = 0.3, ρ = 0.78
25°C sink temperature
2.2 m/sec wind velocity
1003 w/m^2 insolation

Legend:

1-5/8" OD receiver tube 1.495" I.D.
9' x 12' collector, 90° rim angle
α = 0.95 ϵ = 0.30 ρ = 0.78
77°F sink temperature
5 mph wind
318 BTU/ft^2 hr insolation

Figure 4

As has been illustrated, the 260°C plots from Figures 2 and 3 can be used within minimal ΔT error for a collector string inlet temperature range from 204°C to 316°C. A small error may accrue if the efficiency data are used.

Determination of Maximum Allowable Flow Rate

If some fraction of the energy collected, say 1 percent of the maximum, is allowed for pump work to drive the liquid through the collectors, the maximum velocity and volume flow rate can be established as shown in Appendix B. The pump work limit, for liquid flow through a collector using the results from Appendix B, is shown in Figure 5. Using the presented data, the maximum allowable flow is 0.00258 m^3/sec. Should a 0.0318 m plug be used, the maximum allowable flow would be 0.000661 m^3/sec.

These data hold for contiguous collectors. Should collectors be separated as in a north-south field layout, in which each collector individually tracks the sun, the interconnecting fluid lines between them would lose energy due to thermal losses and pumping losses. An approximation of these losses, which results in decreasing the maximum allowable flow rate, is also shown in Figure 5.* East-west contiguous collectors will also have some line thermal and pump losses but not of the magnitude of the north-south arrangement.

The result of these considerations is that more collectors, for a horizontal surface construction, can be used in an east-west string than in a north-south string due to these interconnecting line losses. Each situation must be individually calculated to determine its flow limits; however, 20 collectors in an east-west series appear feasible before the 1 percent limit is exceeded.

For the collector design given in Figure 3, the resulting pump work calculations are as shown in Table I. In the situation of Condition 7, 20 collectors in series would exceed the 1 percent energy limitation.

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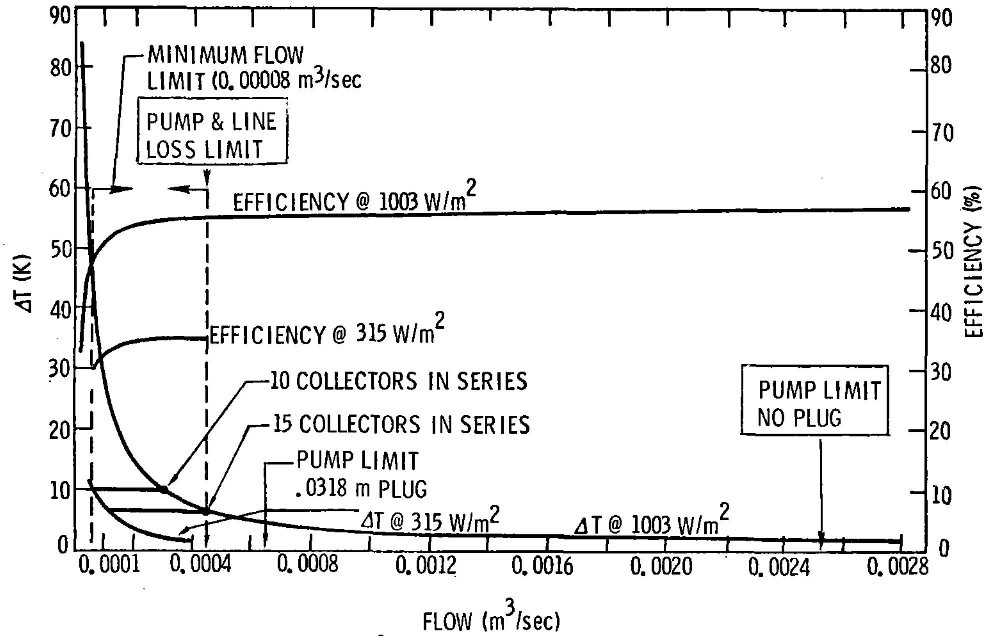
*By comparison of the pump limits and the pump and line loss limits



GIVEN: 260°C
1-11/16" OD TUBE (0.0429m OD TUBE)
9" x 12" REFLECTOR (2.743m x 3.658m REFLECTOR)
α = 0.95 ϵ = 0.3 ρ = .78
90° RIM ANGLE
25°C SINK TEMP
2.2 m/sec WIND VELOCITY

Figure 5

TABLE I

Pump Work Calculations for Data From Figure 3

Condition	Field Array	Plug Diameter (m)	Solar Insolation (W/m^2)	1% Energy Available To Pump (w/collector)	Liquid Velocity (m/sec)	Allowable Max Flow Rate (m^3/sec)	Desired Max Flow Rate (m^3/sec)	Desired Liquid Velocity (m/sec)	Energy to Pump to Achieve Needs (w/collector)
1	10 Collectors In Series	0	915	7.07	1.77	0.002021	0.000216	0.19	0.008
2		0	599	4.07	1.47	0.001680	0.000125	0.11	0.002
3		0.0318	915	7.30	1.22	0.000418	0.000224	0.66	1.15
4		0.318	599	4.27	1.01	0.000346	0.000130	0.38	0.224
5	20 Collectors In Series	0	915	7.21	1.78	0.002033	0.000440	0.39	0.075
6		0	599	4.21	1.49	0.001700	0.000255	0.23	0.015
7		0.0318	915	7.33*	1.22	0.000419	0.000445	1.30	8.99*
8		0.0318	599	4.33	1.01	0.000347	0.000265	0.78	1.90

*Need exceeds 1% energy limit.

For the conditions considered, 20 collectors in series are probably the maximum number which should be used. The determination of the number of parallel rows then is then calculated by dividing the total energy needs by the energy gain from one string of collectors in series.

The data shown in Figures 2 through 5 are based upon normal insolation. These data are applicable to conditions other than normal insolation by applying the cosine angle effect. Therefore, north-south collectors that are not fully sun-tracking and east-west collectors can still be analyzed using these Figures [e.g. with the sun at a 41^{o} angle from normal, the insolation would be (1003 W/m^2) (0.75471) or 757 W/m^2].

Summary

A technique has been developed whereby the number of columns and rows of collectors, north-south or east-west, required to achieve a given task can be determined. This technique is based upon the establishment of a minimum volume flow rate, for the conditions considered, of 0.00008 m^3/sec because of a collector efficiency decrease. It also permits the establishment of a maximum volume flow rate, for the conditions considered, of approximately 0.00045 m^3/sec. This limit is based upon an arbitrary pump work and line thermal loss amount. Extrapolations and interpolations of these results can be performed depending upon the establishment and use of other designs and conditions.

References

1. D. O. Lee, W. P. Schimmel, Jr., and J. P. Abbin, Jr., Sizing of Focused Solar Collector Fields with Specified Collector Tube Inlet, SAND74-0295, Sandia Laboratories, Albuquerque, N. M., 1974.

2. The justification is contained in Solar Total Energy Program - Quarterly Report July - September 1974, SAND74-0391, Sandia Laboratories, Albuquerque, New Mexico, November 1974.

3. Unpublished measurement results for 10 milliradian aperature per R. B. Pettit, Division 5842, to the author.

4. M. W. Edenburn, Performance of a Focusing Cylindrical Parabolic Solar Energy Collector: Analysis and Computer Program, SLA-74-0031, Sandia Laboratories, Albuquerque, New Mexico, April 1974.

```
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*****     *DELETE FOCL,310
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APPENDIX B

Velocity and Pump Work Calculations

A. NO PLUG

Energy into Liquid

Collector Surface Area: (9 ft x 12 ft) = 108 ft^2 (10.029 m^2)

Maximum Solar Insolation: 318 Btu/ft^2-hr (1003 W/m^2)

Intercepted Energy: 318 (108) = 34344 Btu/hr
(9853.2 W)

(Figure 2) 10 Collectors in Series; No Plug; Flow of 0.00028 m^3/sec; Efficiency = 54.1%

Energy Gain in Liquid: (0.541) (34344) = 18580.1 Btu/hr
(5443.41 W)

Pump Work

@ 1% Energy for Pump Work: (0.01) (18580.1) = 185.80 Btu/hr
(54.4 W)

@ 17% Turbo-Generator Efficiency: $\frac{(0.17)\ (185.80)\ (778\text{ ft-lb/ Btu})}{3600\text{ sec/hr}}$

= 6.83 ft - lb/sec (9.26W)

Energy Available for Pump Work @ 78% pump Efficiency:

(6.83) (0.78) = 5.325 ft-lb/sec (7.22W)

Velocity Determination

Mass Flow Rate x Head Loss = Available Pump Work

$$\frac{\text{lb}}{\text{sec}} \times \text{ft} = \frac{\text{ft-lb}}{\text{sec}}$$

$$(\rho AV) \times \left(f \frac{L}{D} \frac{V^2}{2g}\right)^1 = 5.325 \frac{\text{ft-lb}}{\text{sec}} \quad (7.22\text{W})$$

where:

$$\rho = 50.46 \frac{\text{lb}}{\text{ft}^3} \ (810 \text{ kg/m}^3)$$

$$A = \frac{\pi (0.12979 \text{ ft})^2}{4} = 0.01323 \text{ ft}^2 \ (0.00123\text{m}^2)$$

f = 0.017[2]

1. Dercy-Weisbach form of head loss equation.
2. Per L. F. Moody, ASME Transactions Vol. 66, No. 8, Nov. 1944, page 671.

$$2g = 64.34 \frac{ft}{sec^2} \quad (1.96 \ m/sec^2)$$

$$L = 12 \ ft \ (3.658m)$$

$$D = 0.12979 \ ft \ (0.0396m)$$

$$\frac{(50.46)(0.01323)(0.017)(12)}{(0.12979)(64.34)} \quad V^3 = 5.325 \frac{ft\text{-}lb}{sec} \quad (7.22W)$$

$$V^3 = 326.49 \ ft^3/sec^3$$

$$V = 6.886 \ ft/sec \ (2.099 \ m/sec)$$

Allowable Flow Rate for 1 Percent Limit

$Q = AV = (0.01323)(6.886) = 0.091 \ ft^3/sec \ (0.00258 \ m^3/sec).$

B. 1.25 IN. DIAMETER PLUG

Energy into Liquid

Collector Surface Area = 108 ft^2 (10.029 m^2)

Maximum Solar Insolation = 318 Btu/ft^2-hr (1003 W/m^2)

Intercepted Energy = 34344 Btu/hr (10062.84W)

(Figure 2) 10 Collectors in Series, 1.25 In. Dia. Plug, Flow of 0.00028 m^3/sec; Efficiency = 55.6%

Energy Gain in Liquid: 0.556 (34344) = 19095.3 Btu/hr (5594.91W)

Pump Work

@ 1% energy for Pump Work: (0.01) (19095.3) = 190.95 Btu/hr (55.95W)

@ 17% Turbo-Generator Efficiency: $\frac{(0.17)(190.95)(778)}{3600} =$

$$7.015 \frac{ft\text{-}lb}{sec} \quad (9.51W)$$

Energy Available for Pump Work @ 78% Pump Efficiency:

$$(7.015)(0.78) = 5.472 \frac{ft\text{-}lb}{sec} \quad (7.41W)$$

Velocity Determination

$$(\rho AV) \times \left(f \frac{L}{De} \frac{V^2}{2g}\right) = 5.472 \frac{\text{ft-lb}}{\text{sec}} \quad (7.41\,\text{W})$$

where:

$$\rho = 50.46 \text{ lb/ft}^3 \ (810 \text{ kg/m}^2)$$

$$A = 0.01323 \text{ ft}^2 = \frac{\pi (0.1042)^2}{4} = 0.00471 \text{ ft}^2 \ (0.00044 \text{ m}^2)$$

$$f = 0.026$$

$$2g = 64.34 \text{ ft/sec}^2 \ (1.96 \text{ m/sec}^2)$$

$$L = 12 \text{ ft } (3.658\text{m})$$

$$De = Do\text{-}Di = 0.02563 \text{ ft } (0.0078\text{m})$$

$$\frac{(50.46)(0.00471)(0.026)(12)}{(0.02563)(64.34)} V^3 = 5.472$$

$$V^3 = 121.69$$

$$V = 4.955 \text{ ft/sec } (1.51 \text{ m/sec})$$

Allowable Flow Rate for 1 Percent Limit

$$Q = AV = (0.00471)(4.955) = 0.0232 \text{ ft}^3/\text{sec } (0.000661 \text{ m}^3/\text{sec})$$

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