Performance Testing of a Solar Energy Collector

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A simplified calorimetry technique was developed for evaluating the performance of a parabolic trough type of solar energy collector. In order to gain some experience with single-axis concentrating collectors, a simple parabolic collector was fabricated.

I. Introduction

There will undoubtedly be many suggestions for rapid evaluation of solar energy collectors emerging as increasing numbers of investigators turn their attention to the problem. This report describes one approach which has achieved its objectives. The main objective was to develop a simple procedure which required a minimum of laboratory apparatus. A second objective was to devise a simple technique for fabricating a parabolic trough type of solar energy collector.

II. Parabolic Collector Design

The basic approach in the fabrication of a parabolic collector was to machine parabolic ribs in a programmed milling machine; these ribs were then attached to a torque tube as shown in Fig. 1. Aluminum sheets 3.2 mm (1/8 inch) thick were then rolled to the appropriate circular radius to match the parabolic shape of the ribs. The preformed aluminum sheets were then bolted to the ribs to serve as the foundation for the parabolic collector. The mirror (not shown) was a 3.2-mm (1/8-inch)-thick sheet of acrylic aluminized on one side (Ram Products: Industrial grade mirror) and was clamped into the structure in a simple manner for easy replacement. The aluminized acrylic mirror had a reflectivity of around 85%, even though the radiation had to traverse the plastic twice. The protection of the mirror by the plastic is a desirable feature for hostile environments and well worth the small sacrifice in reflectivity.

The drive mechanism was not a matter of concern in this phase of the investigations, and a synchronous motor with a gear box was used in conjunction with a chain drive to provide adequate solar tracking. The techniques used enjoyed the experiences of the Minneapolis-Honeywell project (Ref. 1), and the authors are grateful to Dr. J. Ramsey for helpful information.

III. Solar Collector Evaluation

The performance of solar energy collectors may be determined through some simple calorimetric measurements. By supplementing experimental data with reasonable approximations, it is possible to derive a theoretical model which permits the calculation of the performance under various operating conditions.

The analyses described here are particularly adapted to cylindrical trough collectors.

As stated previously the detailed design and fabrication of solar collectors have been discussed in considerable detail in the literature (Refs. 1 and 2). The purpose here is to consider the evaluation of the performance of any given solar thermal system. A simplified calorimetric procedure is suggested as shown in Fig. 2. Instead of using the usual flowing fluid for measurements, a solid rod of metal, such as aluminum, is used for calorimetry.

The thermal balance equation for Fig. 2 is given by

$$I_0 A_e \eta_0 \cos\phi = MC\frac{dT}{dt} + aK_1 (T^4 - T_a^4) + aK_2 (T - T_a) \tag{1}$$

where

I_0 = direct normal insolation

A_e = effective area of solar collector per unit length

η_0 = optical efficiency

ϕ = angle of incidence of solar radiation relative to surface normal of collector

M = mass of aluminum rod

C = specific heat of aluminum rod

T = temperature of rod in kelvins

T_a = ambient temperature

a = surface area of aluminum rod per unit length

K_1 = radiation loss parameter

K_2 = convection loss parameter in linear approximation.

The motivation for the present approach is the observation that the insolation is substantially constant between 10 a.m. and 2 p.m. on a clear day. For a polar-mounted collector, the solar angle ϕ is also constant; hence, the input is an easily measured constant for any given clear day. Under these circumstances the nonlinear heat balance equation may be solved in various approximations as discussed below.

IV. The Linear Approximation

It is well known that for small variations in temperature the radiation loss term in Eq. (1) may be approximated as

$$aK_1 [(T_0^2 + T_a^2)(T_0 + T_a)](T - T_a) \tag{2}$$

where T_0 is the mean operating temperature. Thus, for small variations in T about T_0, the radiation loss may be combined with the linear loss term in Eq. (1), or

$$I(t) = MC\frac{dT}{dt} + aK(T - T_a) \tag{3}$$

where K is a new constant which accounts for all losses and

$$I(t) = I_0 A_e \eta_0 \cos\phi \tag{4}$$

Although Eq. (3) is applicable for a relatively small temperature range, it is exactly solvable even for the case when insolation $I(t)$ is a variable (cloudy day). Some insight into the dynamics of a solar collector could thus be gained.

V. Nonlinear Approximation

An alternative approximation to Eq. (1) is to assume dominance of the radiation loss term; then

$$I(T) = MC\frac{dT}{dt} + aK_0 (T^4 - T_a^4) \tag{5}$$

where K_0 is adjusted to account for all thermal losses. Equation (5) is applicable especially to high-temperature operation of a collector. Figure 3 shows a typical heating curve for constant insolation. The first deduction from Fig. 3 and Eq. (5) is that initially there are no losses because $T = T_a$. Thus,

$$MC\left(\frac{dT}{dt}\right)_0 = I_0 A_e \eta_0 \cos\phi \tag{6}$$

where $(dT/dt)_0$ indicates the initial slope at t = 0. All quantities in Eq. (6) are known except η_0, the optical efficiency, which is given by

$$\eta_0 = \rho\tau\alpha = \frac{MC\left(\frac{dT}{dt}\right)_0}{I_0 A_e \cos\phi} \tag{7}$$

where

ρ = mean reflectivity of mirror

τ = mean transmissivity of glass tube (see Fig. 2)

α = mean absorptivity of pipe

The second observation from Fig. (3) and Eq. (5) is that when thermal equilibrium is achieved, all the solar power incident on the receiver pipe is reradiated as infrared power and

$$K_0 = \frac{I_0 A_e \eta_0 \cos\phi}{a\,(T_s^4 - T_a^4)} \tag{8}$$

where K_0 is the hitherto unknown loss parameter, and T_s is the stagnation temperature. All quantities in Eq. (5) are now known, and for any operating temperature, T_0, the thermal power available is given by

$$\begin{aligned} P_t(T_0) &= MC\left(\frac{dT}{dt}\right)_{T=T_0} \\ &= I_0 A_e \eta_0 \cos\phi - aK_0\,(T_0^4 - T_a^4) \end{aligned} \tag{9}$$

By combining Eqs. (8) and (9), it is possible to obtain a simple expression for thermal efficiency η_t:

$$\eta_t = \frac{T_s^4 - T_0^4}{T_s^4 - T_a^4} \tag{10}$$

VI. Test Results

Preliminary results indicate that stagnation temperatures up to 400°C are readily obtained with the parabolic trough collector shown in Fig. 1. An aluminum rod 3.8 cm in diameter, coated with black chrome, was mounted at the focus within a pyrex tube. The receiver rod was thus operated with or without a vacuum environment. The temperature of the rod was measured as described previously and typical results are shown in Fig. 4.

References

1. *Research Applied to Solar-Thermal Power Systems*, Report NSF/RANN/SE/GI-34871/PR/73/2, prepared by University of Minnesota and Honeywell, Minneapolis, Minn., July 1973.

2. Duffie, J. A., and Beckman, W. A., *Solar Energy Thermal Processes*, John Wiley & Sons, Inc., New York, 1974.

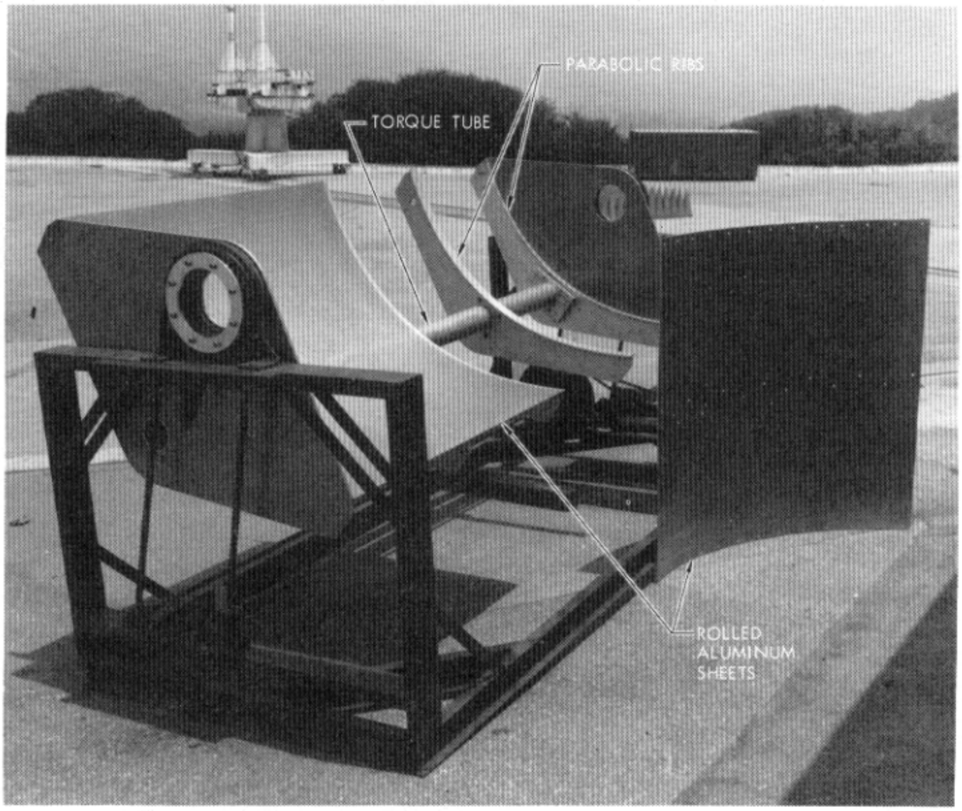

Fig. 1. Construction of parabolic solar energy collector

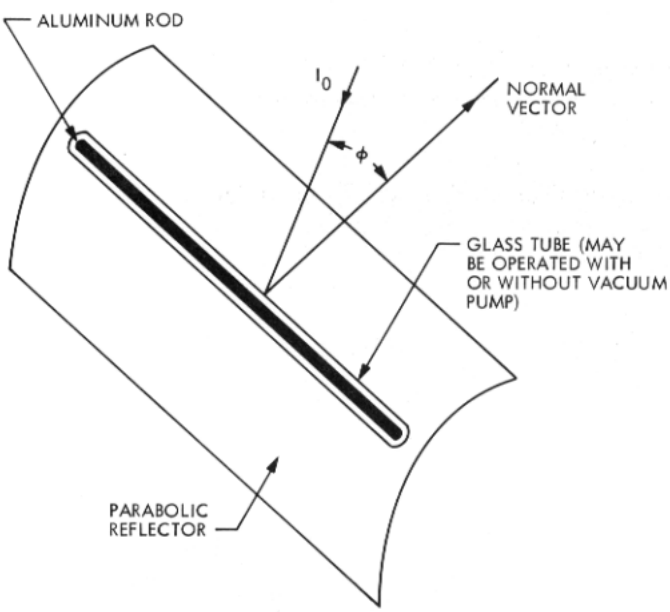

Fig. 2. Test configuration for solar collector

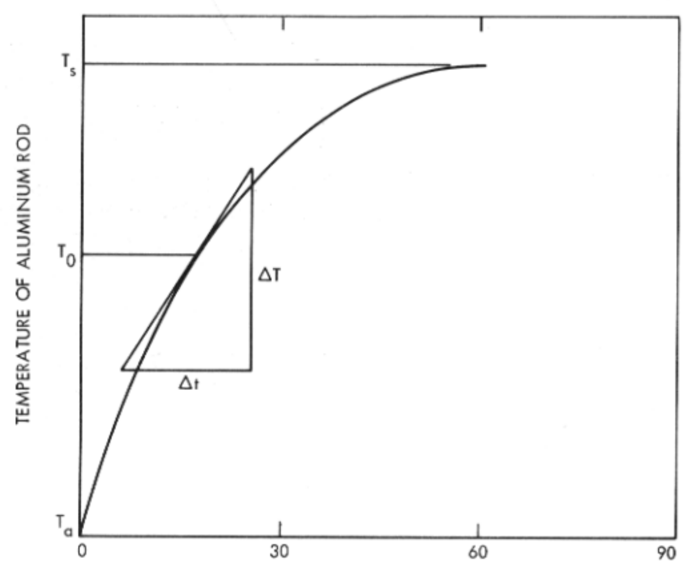

Fig. 3. Heating curve for aluminum rod

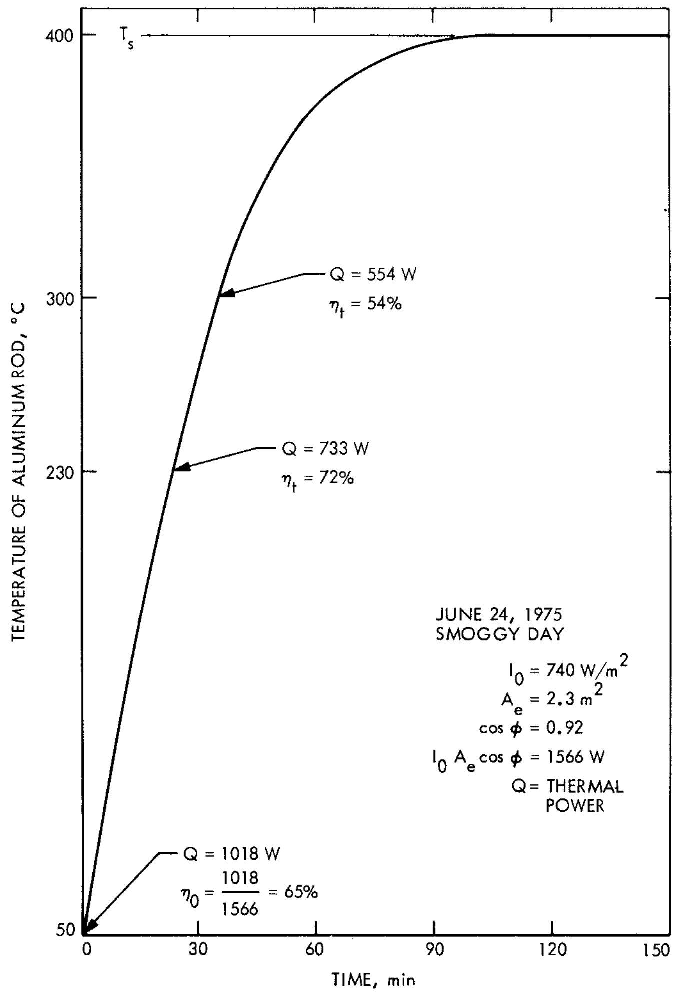

Fig. 4. Typical experimental result (with vacuum)—the values of Q are derived by measuring the slopes (dT/dt) for the specific temperature (Note: Thermocouple nonlinearity is apparent)