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SOLAR ENERGY CONCENTRATION

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ABSTRACT

We have been investigating the optical and thermal properties of ideal concentrators which concentrate radiation by the maximum amount possible for a given range of angular acceptance. This has been done experimentally, analytically and numerically (with the University computer). The following reflector-absorber combinations have been studied:

a) Flat receiver, parabolic reflector (compound parabolic concentrator, or CPC)

b) Vertical fin receiver inside half-aluminized evacuated glass tube coupled to CPC

c) Vertical fin receiver, circular-parabolic reflector

d) Circular cylindrical receiver, extended involute reflector

e) Convex receiver, lens at entrance aperture, hyperbolic reflectors

f) Arbitrary receiver shape, CPC modified to limit angle of incidence onto receiver

g) Concentrators with a gap between the receiver and the reflector for thermal isolation

h) Concentrators used as a second stage concentrator

i) Concentrators formed from a solid dielectric material

In addition to laboratory and theoretical studies of solar energy concentrators, we are in the process of manufacturing a collector to provide heat for a schoolhouse near Gallup, New Mexico. The design is of type (c) with a gap between the receiver and the reflector. Fluid flows through a tube mounted in the fin. We anticipate having the system in operation for the coming heating season.

ERDA Annual Report

This report will describe the work we have done while being funded by ERDA contract E(11-1)-2446 and relate that progress to the program plan we submitted last year. There are six major areas listed in our proposed schedule and these will be discussed in order, after a brief description of our personnel.

Our staff has been steadily increasing, although it is still fairly small. We began the fiscal year with two faculty members, Roland Winston and Lennard Wharton, and one graduate student, Kent Reed, whose main effort is at ANL. In early October Nancy Goodman, a full-time scientific assistant, joined the group. When Kent Reed completed the work for his doctorate and began devoting full-time to the Argonne effort in late January 1976, he was replaced by Frank McGue, also a graduate student. Manuel Pereira, another graduate student, began working with us in early March. We are currently investigating the possibility of hiring a PhD in materials science. This person would benefit us greatly in the thermal program (selective absorbers, transmitting and reflecting materials) as well as in any photovoltaic concentration activity that we may undertake.

A. Basic Optical Design

The basic principle of our concentrator designs is that extreme rays (those forming an angle $\pm\theta_{max}$ with the optic axis of the concentrator, where θ_{max} is its acceptance half-angle) must be directed to the edge of the absorber. All rays within the range $-\theta_{max}$ to $+\theta_{max}$ will then strike the absorber. The particular shape of the absorber defines the differential equation, whose solution gives the reflector shape. All concentrator types discussed below are ideal since their concentration ratio is:

$$X = \frac{n}{\sin\theta_{max}}$$

where n is the index of refraction of the medium filling the concentrator. The first concentrator designed this way was the compound parabolic concentrator (CPC) whose two parabolic sections each focus the radiation incident parallel to their own axis at the base of the other reflector, which is coincident with the edge of a flat absorber.

For thermal considerations, it is beneficial to have the receiver inside a glass tube. This presents the possibility of silvering the back half of the tube and having it serve as a secondary reflector onto a flat absorber along the optic axis of the CPC. We refer to this receiver type as a vertical fin. It has the additional advantages that insulation behind it is not necessary and that its radiating area is half that of a flat receiver of the same absorbing area.

A distinct reflector shape has been designed for a vertical fin receiver. It also consists of two parabolic sections whose axes are inclined at θ_{max} to the concentrator's optic axis, and their foci coincide at the tip of the vertical fin receiver. A circular section is at the base of the fin and extends out to the shadow points (those points where extreme rays entering at the edge of the concentrator aperture strike the reflector). A circle is the involute of a straight line, so any ray reflected off the circle will reach the vertical fin. The reflector is continuous in both position and slope where the circle meets the parabolae.

A reflector shape has also been developed for a circular cylindrical receiver following the same principles. Between the shadow points is the involute of a circle. Beyond them is a curve which is defined by the property that extreme rays must be tangentially incident upon the tube receiver. This curve, also, is continuous in position and slope at the shadow points. A tube receiver is particularly well suited to thermal applications in that a hot liquid can be circulated through the tube and the entire absorber is in direct contact with the liquid.

Much shorter concentrators are possible if a lens is placed at the front aperture. The lens will focus extreme rays at $\pm\theta_{max}$ to the optic axis to perfect point foci at $f_{\pm\theta_{max}}$. The mirrors must be hyperbolae (straight lines are degenerate hyperbolae), each of which have one focus at $f_{\pm\theta_{max}}$ and the other at the base of the opposite mirror.

By filling the concentrator with a medium of index of refraction, n, the effective acceptance angle, θ_{max}, becomes:

$$\theta = \text{arc sin}\,(n \sin \theta'_{max})$$

for the same concentration ratio where θ'_{max} is the design acceptance angle. This is due to refraction of radiation at the air-medium boundary. For large concentrators or those with a convex receiver protruding into the collector itself (like tube or vertical fin receivers), it is probably impractical to have a solid concentrator. However, for small collectors with flat receivers, the advantages are great.

During the course of related work supported by the University, it was discovered that all rays within the acceptance angle are incident on the concentrator wall outside the critical angle of the dielectric medium, thus guaranteeing total internal reflection at the air-dielectric interface, if the acceptance angle is within limits determined by the index of refraction of the dielectric medium used. This provides perfect mirrors and eliminates the necessity of a metallic coating. Accurate piece parts can be molded and be usable with no further work on them.

Lens-mirror systems can also be made from solid dielectric materials. By making the front surface convex, rather than flat, it will become a lens. Thus a single component will form both lens and the reflectors. There will be a total internal reflection of all rays within the acceptance angle at the side walls.

CPC's can also be used as second stage concentrators for focusing mirror systems. In this case, the source is relatively close and has a full angular width of 2ϕ. The maximum concentration that the second stage concentrator can have is $\frac{1}{\sin\phi}$, but even for $\phi \sim 30^{\circ}$, this is a factor of two increase. Because of the total acceptance of radiation within their acceptance angle, ideal concentrators funnel all of the radiation from the primary concentrator onto an absorber.

It is sometimes advantageous to limit the angle at which radiation is incident on the receiver since the absorptivity is a function of angle. To do this, one must limit the angle that the tangent to the reflector makes with the optic axis of the concentrator. If the radiation is restricted to exit within the angular range $|\theta_{out}| \leq \theta_2$, and the acceptance angle is θ_1, then the concentration ratio is:

$$X = \frac{n \sin \theta_2}{\sin \theta_1}$$

which is only a slight decrease in concentration even for limits as stringent as $|\theta_{out}| \leq 70^{o}$. This is compensated for by a decrease in reflection of radiation by the receiver. For solid dielectric CPC's with $\theta_2 < \frac{\pi}{2}$, θ_1 can be increased while staisfying the condition of total internal reflection of all accepted rays at the side walls.

Although optical efficiency is optimized when the reflector and absorber are contiguous, thermal considerations make it necessary to create a gap between them. This can be accomplished in five ways:

(i) Unchanged reflectors, depressed absorber. This configuration is free from optical losses but entails thermal or mechanical problems in practice. There are increased convective and conductive losses due to the larger area, and it is impractical for an evacuated glass tube surrounding the receiver.

(ii) Unchanged reflector with truncated absorber. Optical losses are equal to g/a, where g is the width of the combined gaps and a is the separation of the reflectors at their base or the width of an untruncated absorber. (These definitions hold throughout.) Thermal losses are low.

(iii) Reflectors translated apart with truncated absorber. Thermal losses are the same as in (ii), but optical losses are decreased to ~.4 g/a if the reflectors are translated by an amount equal to g. This keeps the focus of each reflector at the edge of the absorber.

(iv) Vertical fin receiver inside half-silvered glass tube translated towards front of CPC. Thermal losses are lower than in (ii) and (iii) because the actual receiver is half the size for the same absorber area. Optical losses can be kept to ~.8 g/a since the fin extends above the center of the tube.

(v) Reflector truncated near absorber, absorber unchanged. Optical losses are ~.3 g/a and thermal losses are the same as in cases (ii) and (iii).

Types (ii), (iii), (iv) and (v) are particularly well suited for having an evacuated glass tube surrounding the receiver.

These considerations hold not only for the single stage CPC, but for other configurations as well, for example, concentrators with restricted exit angles and arbitrary absorber shapes, and second stage concentrators with finite sources. Further modifications are discussed which may be relevant for special applications.

B. Optical Bench Model Tests

We have been continually making optical tests of various reflector types with our "Light Box System." The system consists of a white box which diffusely illuminates a sample located at one end and a telescope and photomultiplier tube at the other end to detect reflected radiation from the sample. If radiation entering the concentrator at an angle ϕ is absorbed, then none will reemerge at that angle. The output of the photomultiplier tube is proportional to the amount of light reflected.

Recently we have been investigating ways of making collectors in quantity. Those made by any mass production technique are of necessity of a somewhat poorer shape definition than those made one at a time due to errors unavoidable in any replicating process. It should be made clear that these collectors are actually quite good, but they can not be competitive with individually machined prototypes.

It has been discovered that the alignment of the light box system becomes more critical with lower accuracy collectors. A great deal of time has been spent evaluating this problem and carefully aligning the system. We have moved the entire laboratory and acquired a new telescope and detector so the lengthy process of aligning the system has had to be undergone several times.

Specifically, we have had two-dimensional CPC's vacuum formed from plastic and aluminized in sets of four adjacent troughs and have been testing these with flat receivers, vertical fin receivers inside half-aluminized glass tubes, and with black velvet draped into a cavity shaped receiver (reflectivity is lower than for a flat object). We have tested these CPC's both with and without a gap between reflector and receiver and have satisfied ourselves that the optical losses due to the gap are small.

The University shop has built a CPC of highly polished aluminum bent across milled aluminum supports which we have tests and found to be excellent. We have a set of flat and vertical fin receivers with a half-aluminized glass tube, and will soon begin testing the effect of a gap between the reflector and absorber systematically. Since the mirrors are moveable, we can also test the effect of spreading them.

We are also preparing to test lens-mirror combinations. For even moderate size collectors a fresnel lens is necessary due to bulk and weight considerations. We have combined a fresnel lens with matched mirrors and a black velvet cavity shaped receiver and will commence quantitative testing shortly. Preliminary qualitative analysis of the lens mirror combination indicates that for certain configurations, it will provide a good simple way of making an ideal concentrator, although there are present aberrations for skew rays inherent in any cylindrical lens system.

C. Ray Tracing Studies

Our basic ray tracing program has been made extremely powerful and versatile. It can stimulate a source of any angular width, ranging from collimated to totally diffuse illumination; as well as either air filled mirrors or solid dielectric material comprising the concentrator. It can give the distribution of position on the absorber and angle of incidence onto the absorber for the exiting rays. It also gives the average number of reflections that the rays undergo on their path to the absorber as well as what fraction of the light is absorbed by the mirrors or leak through the air-dielectric interface and how many rays are lost in gaps between the reflector and absorber if these gaps are non-zero in width.

Subroutines are written for each specific collector-receiver configuration. Already developed are those for straight sided vee-trough collectors and compound parabolic concentrators, both with flat receivers. In progress are subroutines for a vertical fin receiver in a fin-involute-parabolic collector and for a fin receiver inside a semicircular reflector which can be coupled to any collector shape. In the future a subroutine will be written for a tube receiver inside an extended tube-convolute collector. It is also hoped that we will soon be able to incorporate errors in reflector shapes into the programs, although totally new programs may be necessary for this.

D. Materials Evaluation:

We are still awaiting the arrival of some equipment, ordered in December, 1975, which is critical to our performance of the rigorous testing we have planned. We will investigate the reflectance and transmittance of materials as a function of both wavelength and angle of incidence of radiation. We will be studying wavelengths in the range of 0.3μ to 15μ utilizing separate techniques for the optical and infrared spectral regions. Testing will begin shortly after the equipment arrives.