A Low-Cost Solar Dish Design Utilizing a Stretched Membrane Reflector

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Abstract
The diffuse nature of solar energy presents a continuing challenge for active designs that would harness higher energy levels for applications such as traditional Rankin steam cycles, Sterling heat engines, concentrating photovoltaics, adsorption cycles for cooling , etc.
While the projected cost of traditional non-renewable energy sources is expected to continue rising, the cost of delivered solar energy must also decrease for active solar applications to achieve widespread economic success.
This paper discusses the design progression of a stretched membrane concentrating dish whose design goal is to reliably achieve maximum concentrating capability with the lowest cost of materials.
This design utilizes reflective polymer film, stretched across a rigid, round 45" diameter frame. A vacuum is applied inside to induce a concave shape to the film for the purposes of focusing solar radiation to a concentrated spot. Support of the film is circumferential, only with no underlying support material utilized. The resulting design delivers 130-150 suns of concentrated sunlight to a 4-6" spot at temperatures over 1000F. Problems with the frame design, film wrinkling, and thermal stability in differing ambient temperature conditions are discussed. Actual materials costs recorded is \$ 24/M^2 at retail pricing levels. Weatherable film materials would more than double the cost. Labor costs are postulated, but more difficult to determine.

1. Introduction

Reflective polymer membranes offer an inexpensive method of presenting a large reflective surface area to solar radiation. One methodology is to stretch the reflective membrane across a round chamber, and pull a vacuum inside to induce a concave shape for focusing the solar radiation. While this method has been utilized since the early 1960's[1] most designs utilizing this arrangement have made accommodations to address intrinsic problems associated with construction of such dishes. Some have utilized rings as the basic structure, while others have found that drums provide a greater depth for the deformation of the reflective film.

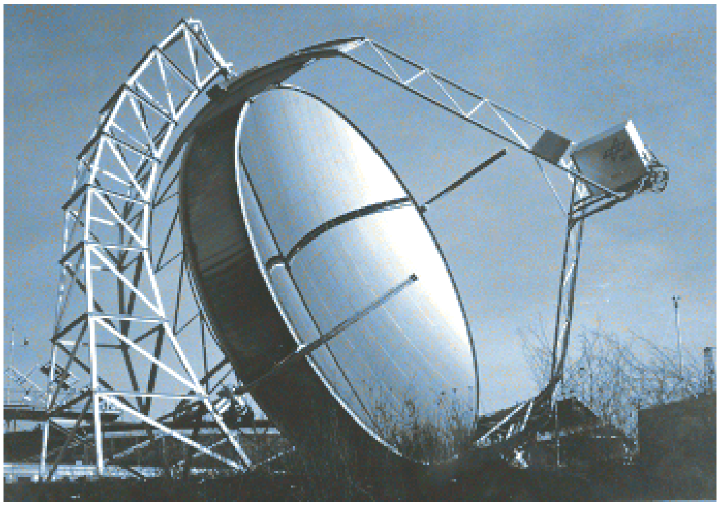

Fig 1- Drum-type dish. Schlaich, Bergermann und Partner 7.5 M stretched-membrane concentrator[2]

Any large ring or drum can undergo ovaling from the perfectly round condition due to its own weight, or due to wind load. External support of the round ring or drum is often required via the mounting structure behind the reflector. Aanother way of preventing ovaling is to provide circumferential support via cables, similar to the spokes of a bicycle wheel.

Fig 2- Cables guyed to central hub. Solar Kinetics 7-m prototype single-facet concentrator.[2]

Smaller dish diameters minimize the forces that induce geometric ovalling or warping. Additionally, smaller dishes can be arrayed to approximate a parabolic shape, minimizing the amount of distortion that needs to be induced into the reflective membrane of any one dish.

Fig3- Smaller dishes arrayed to focus onto a single receiving point. HTC Solar Research Concentrator[2]

Dish Design

A 45" diameter was chosen for initial design investigations[3].

The dish design presented overcomes the ovaling problem by attaching a round plastic ring to a structural foam board backplane material, which prevents ovaling of the ring. Additionally, the ring prevents non-uniform warping or "potato chipping" of the backplane material. The ring and foam board back plane are mutually supportitive, and result in a raised circumferential planar surface for the attachment of the reflective film.

Fig. 4- Ring/Backplane frame design

Past designs have utilized a second film to seal the back of the assembly. The semi-rigid foam board backplane provides this sealing surface, and also minimizes the depth required of the final assembly to provide for clearance for deformation of the reflective film. A 2" raised circumference is all that is required for achieve an 8-10' focal length. The backplane thickness is sized so that it will undergo some small amount of uniform spherical deformation when vacuum is applied. The completed dish assembly is considerably stronger with a vacuum applied and is self-supporting as a unit. External support structures are required for mounting only.

Film Problems

Polymer film stretches easily in one direction, but wrinkles badly when stretched in several directions, such as when a vacuum is pulled on a film that is tightly stretched across a round raised ring. [3] In this instance, the wrinkles propagate inward, scattering a significant amount of the radiation away from the desired focal point. The wrinkling force is at the maximum, and wave form its smallest where it begins at the circumference. As the wrinkle spreads inward, the force becomes less, and the waveform shallower and wider.

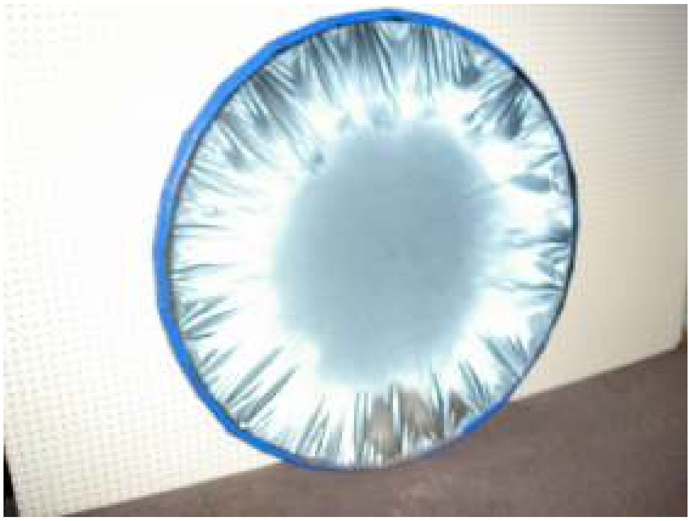

Fig. 5- Winkles typical of 2 mil aluminized film stretched across a tubular ring, with vacuum applied inside.

Many stretched-membrane designs have migrated towards a laminate film that may have a structural foam or a metal sheet attached behind the reflective film, and/or a thin glass mirror attached to the front surface.
This design utilizes a flat annular structural foam board batten to inhibit this wrinkling. This batten is attached to the back of the film just inside the ring diameter and "floats" with the film as it is pulled into a concave form.

Fig. 7- Vacuum applied, with floating annular battens

Thermal stability- The thermal coefficient of expansion differs between the film and the supporting framework, esp. the supporting ring. Operating temperatures cooler than those at which the film was attached to the dish causes the film to become loose. The solution was to place a black heat absorbing material on the face of ring circumference to absorb solar radiation. A conducting layer was placed beneath the absorber to distribute this heat to the ring, and an insulation layer is then placed on top of this. Since the dish is intended to always face the sun during operation, this differential heating is always at work when there is sun. Testing has confirmed a tight reflective surface in temperatures from 25F to 100F.

Fig. 6- Structural foam board batten is attached to the inside of the reflective film to inhibit wrinkles. (photo shows attachment on the outside for clarity)

Fig. 8- Cold (25F), sunny (850 w/m2) day. Dish on left has solar tensioning (black material on circumference). Dish on right without.

Performance
Testing was conducted to determine the amount of heat generated at differing levels of solar radiation as measured with a Daystar meter. The finest focal point noted was app. 4” diameter, at a focal length of 8 feet. A type K thermocouple (washer type) was bolted to the back or a 4” dia. copper plate, which was then insulated.

Fig. 9- Insulated receiving plate
Testing results are noted below:

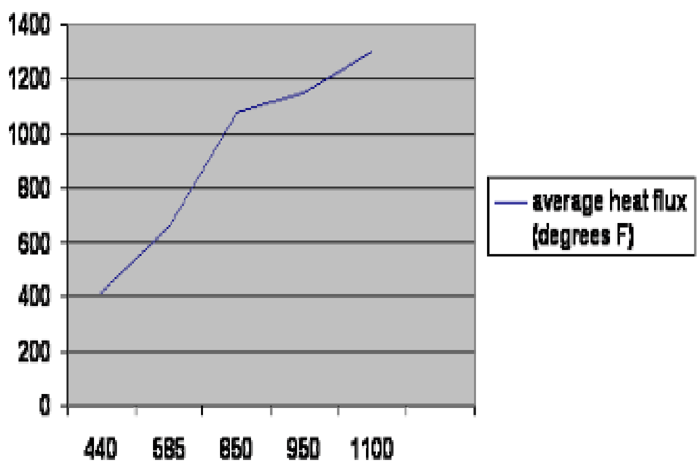

Fig. 10- Temperature vs. solar radiation.

Time to boil 48 oz. of water is 7 minutes at 925 W/M^2

This dish design has not undergone formal specular testing, but spherical aberration can be observed as an array of sub-focal points stretched out just ahead and behind the best total focus spot.

Fig. 10- Focused light directed into inverted oven for cooking.

Energy Overhead Considerations
The energy required to maintain a vacuum inside the dish must be subtracted from the total energy generated. No empirical measurements have been taken re. this overhead requirement, but the focus of the tested arrangement was noted to extend at a rate of app. 12” for every 30 minute period.

Manufacturing Costs
Various cost estimates have been published regarding cost of solar reflecting surfaces (planar as well as concentrating). NREL and Sargent & Lundy estimated heliostat costs of \$94 /m^2 to \$148/m^2 (4). Sandia Labs has estimated a material-only cost of between \$24/m^2 and \$56/m^2 for individual facets (5). Science Applications has invested heavily in vapor deposition and web manufacturing equipment to manufacture reflective material (only) for as low as 10/m^2 (6).
The 45” dish design presented is currently manufactured in low volumes at a materials cost of \$24/m^2, not including mounting hardware and vacuum source. Labor hours currently run 9 hours per assembly, utilizing unpowered rotary fixtures. Powered rotary fixtures that perform multiple operations in each dish rotation could significantly reduce the manufacturing labor.
Although the current dish frame is suitable for continuous outdoor exposure, the film utilized is not. NREL’s Advanced Materials group has identified several film candidates suitable for long-term weather exposure, although these films will likely more than double the cost of the finished dish assembly.
Since this design does not utilize any support under the film surface, survivability in high wind and hail conditions is a concern. A break-away mounting design is envisioned that will weathervane, stowing the reflective side of the dish during high wind and hail events.

Summary
A design progression was undertaken to develop a best-cost stretched membrane solar dish. The frame utilizes a near-perfectly round ring attached to a near-perfectly flat structural foam board backplane, providing a mutually supportative structure. A circumferential plane results for the attachment of reflective film. A vacuum placed inside the enclosed frame causes a concave distortion of the reflective film, resulting in a 4-6” focal spot at a focal length of app. 8-10’. Stiffness of the entire structure is increased upon the application of vacuum.
Wrinkling of the film is minimized by applying a circumferential floating batten to the inside surface of the film.
A solar tensioning system has permitted operation at ambient temperatures from 25F to 95F.
Temperatures of over 1000F at 900 W/m^2 have been recorded onto a 4” diameter copper receiver plate.
Vacuum leakage rates have been reduced to 20% per hour (1 foot of focal length loss per ½ hour).
This design will be scaled up to an 8’ diameter dish in the spring of 06. Long term weathering tests will follow.

References

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