Technical Review of "Ultra Efficiency, High Temperature Solar Collection and Storage"

Reviewed by Sandia Laboratory, PhD, 10 Year Solar Scholar

Overview

Pinnacle is developing several technologies that are designed to efficiently absorb solar energy and provide heat suitable for thermoelectric power production or residential/commercial heating applications. The basic technology under development by Pinnacle is called a Solar Trap, and both tracking and non-tracking embodiments are presented. In practice, a Solar Trap uses spectral and angular selectivity along with a single-pass counter-flowing heat transfer fluid intended to absorb a high percentage of incident solar energy prior to exiting the Trap at a high temperature. The Trap is designed to limit radiative, conductive and convective losses across a wide operating temperature range. What follows is an independent assessment of some of the performance claims made by Pinnacle in "Ultra Efficient, High Temperature Solar Collection and Storage", hereafter referred to as "the Document", and a discussion of design elements that should be considered as the development of Solar Trap technologies continues. Two configurations of the Solar Trap are considered in this technical review: The "low temperature" embodiment, shown in Figure 13 (page 46) of the Document, and the "high temperature" embodiment shown in Figure 11 (page 44).

High Temperature Solar Trap

Description of the device

The high temperature solar trap uses a combination of spectral and angular selectivity to maximize solar collection efficiency even at high temperature (>1,000 K). Relatively collimated sunlight passes through a baffle, possibly with multiple reflections, and ultimately strikes an absorber where it is converted to heat. Re-radiation from the absorber is diffuse, and distributed across an entire hemisphere (2π steradians). Such diffuse radiation does not penetrate the baffle directly, and is therefore better retained by the Solar Trap. Heat absorbed by the baffle itself may be transferred to a fluid, gas or liquid, flowing from the aperture through the baffle to the back of the trap. The fluid moves at a velocity higher than the diffusion velocity of heat within the fluid, thus limiting the conductive transport of heat within the fluid to the top of the trap, where it might otherwise escape.

Use of the solar trap with concentrated solar input

One embodiment of the high temperature solar trap receives solar energy input as concentrated flux from the collection field. Concentrated sunlight is not collimated, but distributed across an angular space proportional to the size of the collector (or collection field), its distance from the receiver, and the optical properties of the reflective elements. This is best illustrated for a perfect reflector focusing sunlight to a "point". The ray trace diagram below shows how concentrated sunlight is distributed at the focal point where the receiver is placed.

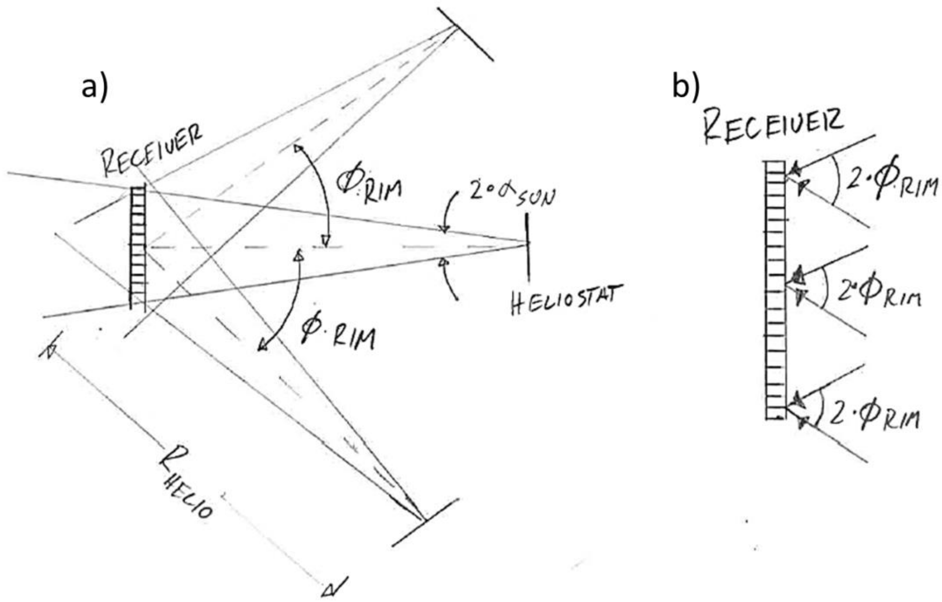

Figure 1. a) Angular distribution of concentrated sunlight from an arbitrary collection field and b) the angular distribution of energy on the surface of the receiver

The angle over which concentrated sunlight is distributed is $2 * \phi_{rim}$, or twice the collector "rim angle". It is the angle over which the collection field is distributed as viewed from a point on the receiver. Generally this is +/- 45 degrees for a dish (90 degrees included angle), and can vary widely for a central receiver. This means that, for a dish, sunlight is distributed across a 90 degree cone at every point on the receiver surface. This is a much wider distribution than the angular extent of the sun ($\alpha_{sun} = 10\ mrad$). When applied to a Solar Trap with a reflective baffle, such a broad distribution would lead to many internal reflections as the light travels through the baffle of the Trap, possible leading to significant thermal losses.

If the solar trap is deployed in a central receiver configuration the collection field must be designed in a way to maintain the overall collimated quality of the incident sunlight. This implies a narrow field (angular basis), or a segmented receiver in which specific sections are oriented to be normal to light incident from specific segments of the collection field (a large field composed of multiple, narrow subfields). There is precedent for this; "secondary concentrators", usually compound parabolic reflectors or refractive systems, are often used with relatively narrow collection fields to increase the geometric concentration ratio of concentrated light from a central receiver collection field in cases where high flux is required (i.e. high temperature processes). In addition, Ron Ace has indicated that he has reached the same conclusions and would use a segmented solar trap, with each segment receiving energy from heliostats within a narrow rim angle, as a means of maintaining a relatively collimated light source while still providing greater than one sun concentration. In this case it will be necessary to use accurate and small heliostats to achieve the necessary optical quality. There is industrial precedent for this in utility scale central receiver projects now underway in the United States.

Collection efficiency of the Solar Trap

The high temperature solar trap analyzed in this study is the embodiment described by Ron Ace in Figure 11 of "Ultra Efficient, High Temperature Solar Collection and Storage". This embodiment is shown graphically in Figure 2 (copied directly from the aforementioned document by Ace). The heat transfer model developed to simulate the trap exploits the symmetry of the device and is limited to a single baffle channel, shown in Figure 3.

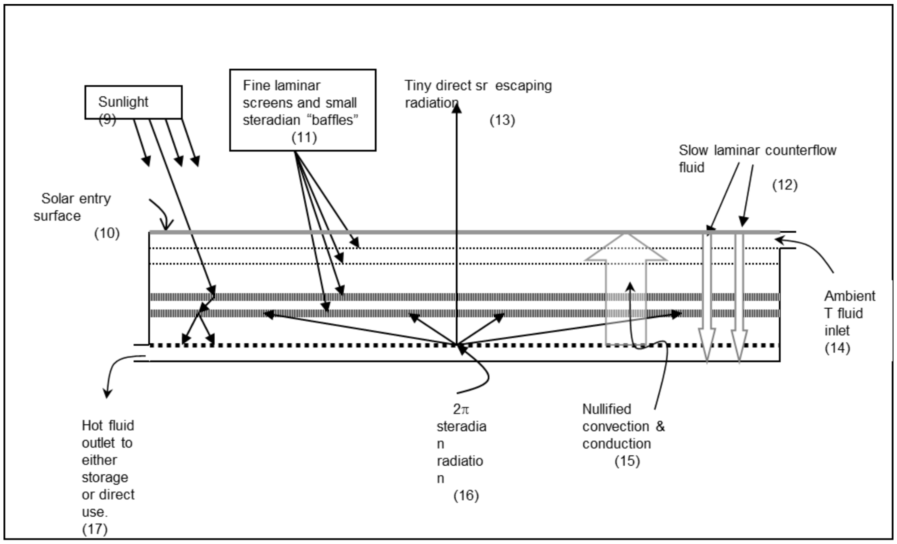

Figure 2. The high temperature solar trap

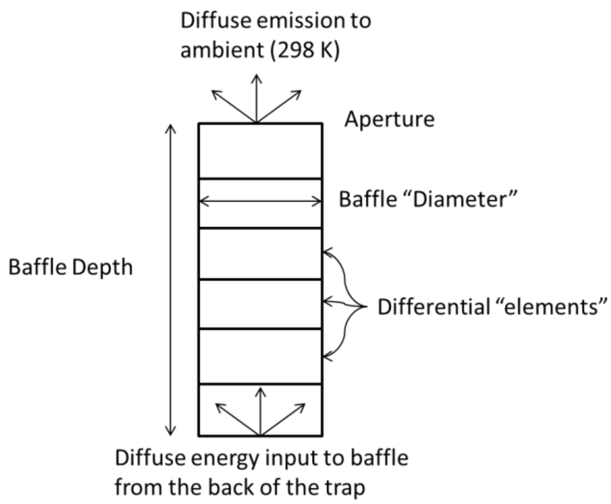

Figure 3. A single baffle channel representative of the simulation domain

In operation, solar energy with a beam divergence of ~10 mrad enters the top of the trap and is transferred through the baffle to the back of the trap at low loss (zero loss assumed in this analysis). The incident solar energy is completely absorbed in the back of the trap and re-radiated from the back to the entrance of the baffle. Some of the energy emitted by the back of the trap escapes directly from the aperture through a narrow solid angle defined by the baffle geometry; the remainder is absorbed by the baffle and transferred through it radiatively, by successive absorption/emission processes. Energy passing through the baffle may be absorbed by a counterflowing heat transfer fluid.

The temperature of the heat that may be extracted from the trap and the efficiency of extraction depend on the temperature distribution within the baffle as this determines the rate of radiative heat loss by diffuse emission to the environment through the aperture (assuming that the narrow solid angle "direct loss" from the back of the trap is very small, which it is in a well-designed trap). The temperature distribution within the baffle is a function of both radiative transport and convective heat removal. Radiative transport in the baffle is analyzed in this report by discretizing a single baffle channel into multiple smaller elements, each of which is connected by a view factor to every other element making up the single baffle channel. This discretization is shown in Figure 3. Analysis in this fashion results in a set of algebraic equations, one for every element and another for the base of the trap, which must be solved simultaneously. Once solved, the ***average*** temperature of each baffle element may be calculated. It is important to understand the implications of the calculation of an average element temperature; in the event that a single element is used to simulate the entire length of the baffle the average temperature calculated for this element does not represent the actual temperature distribution within the baffle. It lacks sufficient resolution. As elements are added, the resolution of the simulation increases and the simulated temperature distribution in the baffle becomes more accurate. The influence of the number of elements used in the simulation on the simulation result is illustrated in Figure 4.

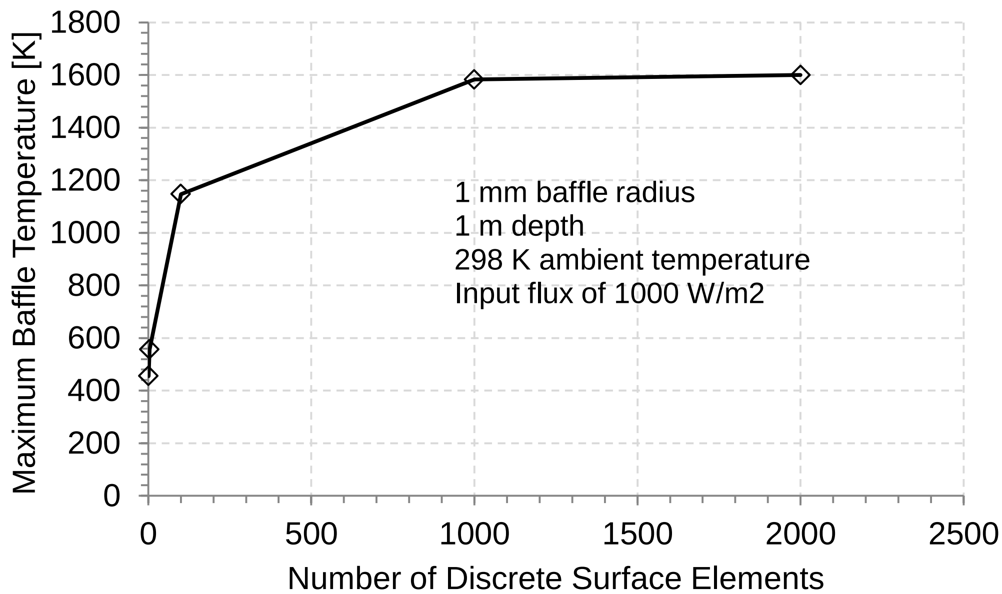

Figure 4. The maximum baffle temperature in the solar trap as a function of simulation resolution.

The results shown in Figure 4 were developed according to the following assumptions, which are consistent for all of the radiative simulations discussed in this report:

1. Power from the sun is incident at 1000 W/m^2 and transmitted to the back of the trap with no loss.
2. The back of the trap radiates diffusely to the entrance of the baffle. Each baffle channel has a diffuse power input of 1000 W/m^2 multiplied by the baffle entrance area as defined by its radius (this applies to baffles with square cross section as well).
3. Energy may leave the baffle as diffuse radiation to the environment, which is assumed to have a temperature of 298 K.
4. Energy may be extracted from the baffle by a counterflowing fluid, although the fluid is not modeled explicitly.
5. The baffle may be operated at the stagnation point, with no heat extraction by the fluid and all incident solar energy rejected diffusely from the aperture. This mode of operation yields the highest possible baffle temperature, but the lowest collection efficiency (e.g. zero).
6. The baffle surfaces are black with respect to thermal radiation (100% absorptivity/emissivity)
7. The aperture of the trap is perfectly transparent. That is, it transmits solar wavelengths and infrared perfectly. In reality, this surface would almost certainly be somewhat selective, transmitting more in the solar band and less in the longer wavelength infrared region. Such a selective surface would increase the temperature of heat extraction from the trap for all operating conditions.

The results in Figure 4 show that if only a single element is used to simulate the entire length of the baffle the maximum temperature of the baffle (and trap) predicted by the model is 400 K. As the number of elements is increased, the maximum temperature predicted by the model increases as well, converging to a steady value ~1600 K only when more than 1000 elements are used along the length of the baffle. At this point the model results are considered to be numerically independent of further increase in the number of discrete elements. This is called “mesh independence” in the numerical analysis community.

The maximum temperature that the baffle can reach is a function of its geometry, among other things. Figure 5 shows the effect of changing baffle depth and radius on the temperature distribution along the baffle, again for the stagnation condition. These results are not representative of Trap performance when heat is actively removed, but do serve to illustrate the upper temperature limit of the device and how the operating temperature is affected by changes to the trap geometry.

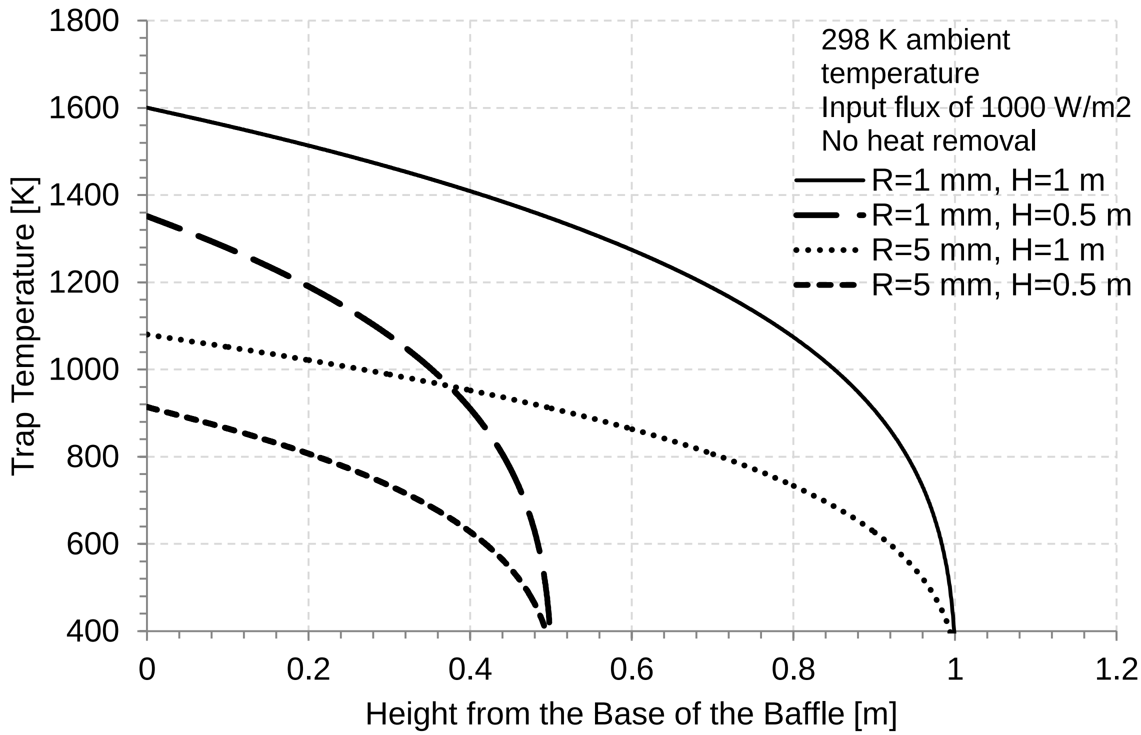

Figure 5. The temperature distribution within the baffle for several geometric configuration. Heat removal is zero (zero efficiency, stagnation condition).

The maximum baffle temperature shown in Figure 5 is roughly 1600 K. Higher temperature is possible with either a deeper baffle or a narrower one. In all cases the temperature distribution is non-linear. The model shows that the baffle responds to geometric changes as expected: the temperature decreases as either the baffle diameter is increased or the baffle length is decreased. Both changes increase the “view” of the aperture by regions deep within the baffle, thus increasing radiative loss.

The true potential of the solar trap can only be fully assessed by explicitly including convective heat transfer in the performance simulation. Convection was not included in this report, but its effect on trap temperature was simulated by applying a constant heat removal rate to the inside of the baffle. A note of caution is needed here: the following results are merely illustrative and do not accurately simulate the effect of convective heat removal on the temperature distribution within the trap and on collection efficiency. In reality, convective heat removal would likely not be uniform, as assumed in this simplified analysis, the goal of which is to show that removing heat does not diminish the temperature of the baffle to a level unsuitable for thermoelectric power generation (i.e. below 700 K). A more accurate prediction of the temperature distribution in the baffle and associated collection efficiency could be developed using standard commercial multi-physics packages such as ANSYS, FLUENT, or COMSOL.

Figure 6 shows the temperature distribution for two geometric configurations when heat is removed from the baffle uniformly along its length. The amount of heat removal is 90% of the solar input, a simulated collection efficiency of 90%.

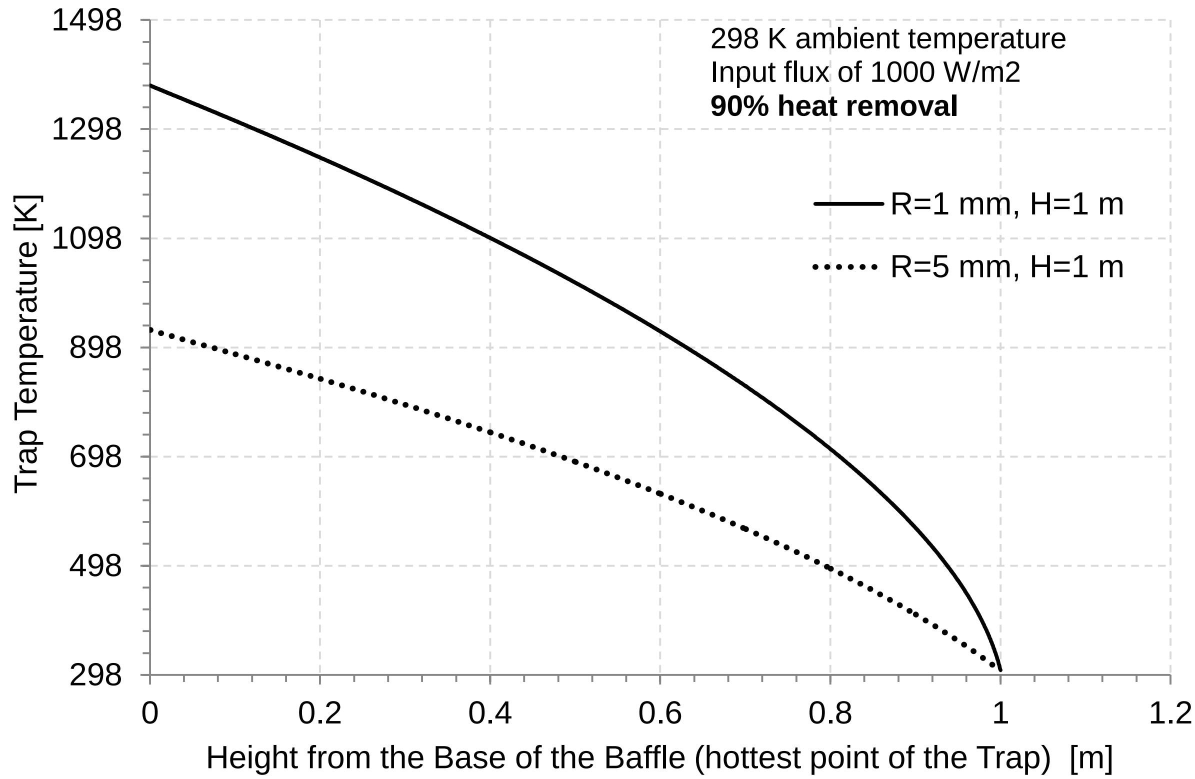

Figure 6. Baffle temperature distribution when 90% of the incident solar energy is continuously extracted from the Trap (90% collection efficiency).

Figure 6 shows that when 90% of the incident solar energy is extracted by a counterflowing heat transfer fluid, the Trap can operate at an outlet temperature of 1375 K for the baffle conditions shown (1 mm diameter and 1 m deep). Even though Figure 6 is based on an artificial treatment of convective heat removal, it serves to illustrate one of the favorable attributes of the Solar Trap: the ability to collect solar heat efficiently, even at one sun, and achieve a relatively high operating temperature.

Low Temperature Solar Trap

Description of the device

The “low temperature” solar trap has a different configuration than the high temperature device; instead of using baffles to limit radiative losses from the collector, the heat transfer fluid (transparent) passes through the incident solar energy multiple times, in a serpentine pattern shown in Figure 7, which is reproduced directly from The Document (note that the fluid passes through the trap only once, but along a serpentine path). The fluid heats progressively as it moves deeper into the collector. Using multiple fluid passes, each within an individual channel, incorporates more surfaces into the device, each of which may serve to limit radiative transport from the device without significantly affecting light transmission into it. To be clear, referring to this embodiment of the Solar Trap as “low temperature” may be a bit misleading; it is in fact theoretically capable of high collection temperature, although in practice possibly not as high as the baffle-based embodiment if for no other reason than that the glass walls between channels are limited to operation below ~1000 K, at which point mechanical strength begins to decrease rapidly.

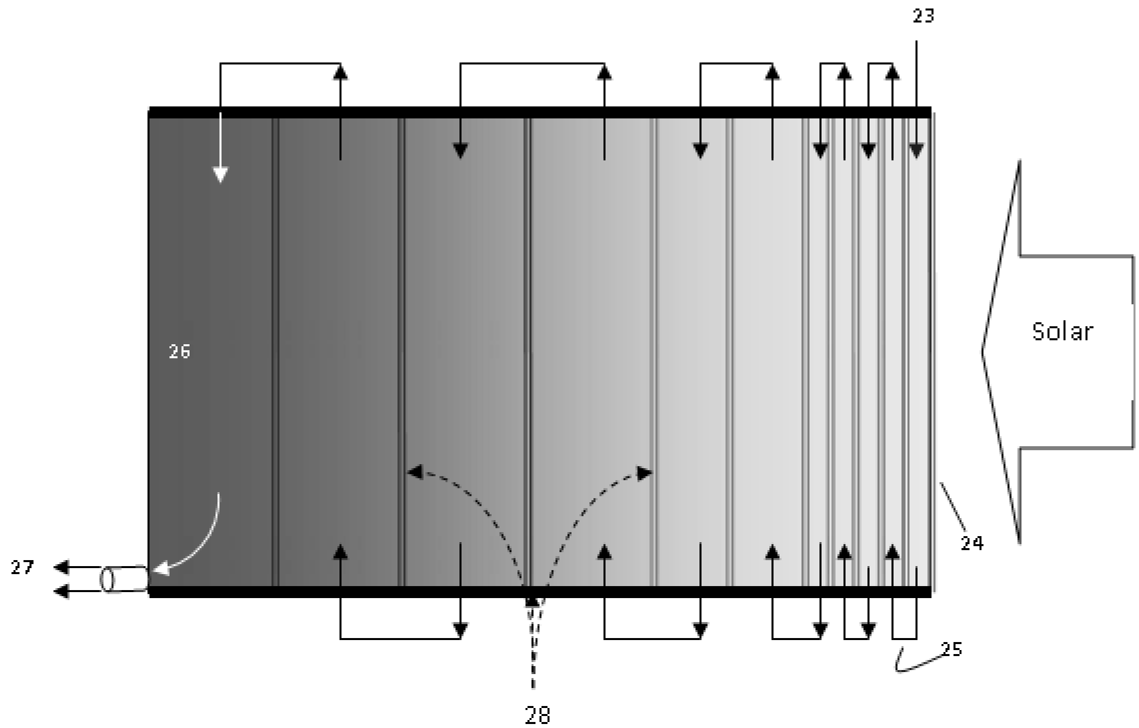

Figure 7. The “low temperature” Solar Trap with a serpentine configuration.

Heating mechanism(s)

In operation, it is likely that relatively little heat will be absorbed directly from the incident sunlight by the heat transfer fluid (if it is water) since the portions of the solar spectrum that are absorbed by water have essentially been filtered out by the atmosphere. Other fluids, having different radiative properties, may be used to change the way light interacts with the Trap. In addition, glass is largely transparent to wavelengths below 3,000 nm. Therefore, sunlight entering the trap would pass through the heat transfer fluid and glass and terminate at the back of the trap, where it would either be reflected or absorbed. In the latter case, the back surface would heat up and begin to re-radiate diffusely to the serpentine channels above. Heat would also conduct through the back of the trap to the surroundings, but this can be limited by a judicious choice of insulation. If the serpentine channel walls are glass, energy emitted by the back of the trap will be absorbed by the first layer of glass it encounters, causing both glass and fluid behind it to heat. Heat transfer then becomes a combination of conductive and radiative transport to successive serpentine channels, with conduction opposed by the motion of a counterflowing fluid and the possible inclusion of a low conductivity gas in between serpentine channels. The result is that, given enough channels and sufficient fluid flow rate, very little heat escapes the aperture, indicating high collection efficiency. Collection temperature can be high as well due to the use of multiple counterflowing channels and spectrally selective channel walls (e.g. glass). The ultimate operating regime of the low temperature Trap configuration may be dependent on the choice of heat transfer fluid; in general, a fluid with low vapor pressure at the desired outlet temperature is needed to avoid complications arising from pressure induced mechanical stress.

Comparison with current tech

The low temperature Solar Trap is compared to current technology in Figure 3 of The Document (page 37). I believe that the analysis presented in the Document is based on the assumption that heat conduction from the interior to the trap to the aperture is eliminated by the use of a counterflowing fluid to oppose conduction. In this case, losses are limited to those due to conduction through the Trap walls and radiation from the aperture, which is mediated by the temperature difference between the aperture cover and the sky. These losses may be low, even compared to a solar input of 1 sun, if 1) the aperture is kept cool by the counterflowing fluid and 2) a low conductivity insulation is used in sufficient thickness and 3) if the means by which the serpentine channels are supported does not present a significant conduction path to the environment. The second requirement, dealing with insulation, is a design choice, and will involve an optimization between performance and cost (i.e. higher quality insulation is more costly). The first requirement, dealing with heat removal by the counterflowing fluid, determines how well heat conduction from the trap to the aperture is blocked. If the flow rate is insufficient, conduction will cause the aperture cover to heat and increase losses. The flow rate itself is defined by the heat capacity of the fluid used in the Trap, the desired temperature increase, and the incident solar flux. One of the examples in the Document (page 47, "Courtesy Collage") states that the flow rate for water undergoing a temperature change of 100 Celsius is 3 cc/s, which works out to a flow speed of 0.3 m/s. Furthermore, as the desired operating temperature of the Trap is increased, the flow rate of the fluid must decrease, further limiting the counterflow effectiveness. It is not clear from the accompanying discussion in the Document that sufficient analyses have been done to explicitly evaluate the effectiveness of limiting heat transfer from the Trap with a counterflowing fluid in the case of the serpentine flow arrangement (it is simply assumed to be sufficient). Such analyses would likely involve an iterative solution for heat conduction and convection within the channels of the Trap, or a more elaborate computational fluid dynamics simulation. Such as analysis is needed to more accurately evaluate the temperature of the "low temperature" Solar Trap, but is beyond the scope of this initial report.

It is my opinion that the performance estimates given on page 37 of the Document for the low temperature Trap most accurately represent the potential performance of the Trap relative to current technology when the operating temperature is in the range of domestic water heating applications. As the operating temperature increases, and flow rate drops, mitigation of conduction with the counterflowing fluid becomes less effective and losses increase, making it more important to explicitly calculate the counterflow effect as a means to ultimately calculating collection efficiency. This is true even when a low conductivity gas is included between serpentine layers; heat will be transferred across the gap by thermal radiation as well. In addition, the performance estimates shown on page 37 of the document are between a theoretical concept with an idealized performance estimate (the Solar Trap), and field performance data for conventional solar heating hardware. It is my opinion that the performance of the Trap, in practice, will be lower than the initial theoretical estimates in the document indicate. How much lower is unclear. What is clear is that the performance potential of the Trap exceeds current, state-of-the-art solar heating technologies operating at 1 sun solar flux input.

Conclusions

General

The primary objective of this technical review and report was to assess Pinnacle's solar inventions, described in the Document, at a level sufficient to identify any clearly evident deficiencies in Pinnacle's designs or errors in their analyses. None were identified. A secondary objective of this work was to identify areas of the design that are particularly critical to realizing the full potential of the solar Traps in the two embodiments specifically investigated, and discuss the relevant technical issues. This has been done in the preceding sections, and it should be noted that the inventors have previously considered many of the issues I identified. In general, I feel that the solar Traps (high and low temperature configurations) are technologies with the potential to achieve high collection efficiency at high collection temperature, even under one sun insolation. The designs are innovative and the analysis generally well thought out. My comments in this report on the potential of the Solar Trap are almost exclusively related to my opinion that more comprehensive analysis of the devices is needed to further refine performance estimates presented in the Document.

High Temperature Solar Trap

In my ten years of experience with solar power and heating technologies I have never encountered a device using the angular selectivity approach embodied by the high temperature Solar Trap as shown in Figure 2. In my opinion, this approach is unique. In theory, it is capable of both high collection efficiency and a high discharge temperature under an incident flux of 1 Sun (1 kW/m^2). This is a compelling combination that certainly merits further development. In my opinion, the next steps for this technology could be done in parallel: the construction of a prototype, baffle-based concept should be undertaken while a more comprehensive computational model is developed to better simulate the performance (collection efficiency and discharge temperature) of the high temperature Solar Trap.

Low Temperature Solar Trap

The performance predictions for the low temperature Solar Trap (fig. 7, above) presented in The Document (page 37) are likely accurate relative to state-of-the-art solar heating technologies for operation at low temperature, consistent with domestic water heating applications. To be clear, the analysis needed to conclusively prove the preceding conclusion has not been done, but it is my opinion that the assumptions made in the analysis to estimate collection efficiency are acceptable for a temperature range consistent with water heating applications. They may be valid for even higher temperature operation, but I'm less certain about this and recommend a more exhaustive heat transfer analysis in which the flow through the device and all relevant heat transfer mechanisms are explicitly modeled.