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RAY TRACING FOR SIMULATION OF A LIGHT GUIDE EFFICIENCY

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ABSTRACT

This work is a feasibility study on using a light guide instead of a heat transfer loop for the energy transfer from the focal point of a concentrator to the heat absorber, The guide consists of two pipe bends, with internal reflecting surfaces. A polar mount setup then allows for single axis rotation where one bend is fixed and the other rotates. The seasonal solar change in declination will then give some variation in the entry angles for the rays at the inlet of the light guide.

Two particular cases have been compared. In the first, the rays enter into the light guide with diverging angles, as the guide is positioned at the focal point of a parabolic dish. In the second case, a secondary reflector generates parallel rays at the entrance of a guide positioned below a central hole in the primary receiver.

The study is made using a ray tracer which has been developed for concentrating solar reflector systems. Energy losses through a light guide can be associated with the number of internal reflections in the guide, and the number of back scattered rays through the tube inlet. The ray tracer is described briefly and sensitivity studies are made with variations in the tube lengths, surface reflectivity and the inlet ray angles.

INTRODUCTION

A heat storage unit is a key element of a solar heat collection system, as the solar radiation is intermittent due to weather changes. A heat storage can be designed to accommodate variations in energy supply and demand during one day or over several days. For concentrating systems this requires then a system for heat transfer from the focal point of a dish, or focal line of a trough, to the heat storage. Several heat transfer methods are possible, with heat transfer media being air, water or oil and with forced (pump or fan) or with natural circulation in heat transfer loops.

With direct illumination of the heat storage, the heat transfer loop is bypassed, and the associated heat losses are reduced. This benefit may come at the expense of more complex reflection systems. If a heat storage is of a large dimension, it also needs to be in a fixed position, whereas the reflector has to move with the sun to be in focus. Fixed focus systems can be achieved with offset reflectors (e.g. Scheffler reflectors), where the storage can be illuminated form the side. Top illumination of a storage can be achieved using a secondary reflector which reflects the rays back through a hole in the primary reflector and onto a heat storage positioned below the primary reflector. However, during the daily sun tracking, the rays will then hit the top surface at an angle, and the top surface will also be exposed to heat losses to the ambient.

A light guide could serve as a heat transfer method, by guiding the solar rays though a pipe with an internal reflecting surface and onto the absorbing surface of a heat storage. Signal transfers in the form of light are used in optical fibres, where absolute reflections on the wall give close to loss-less transmission. This is possible if the fibre material is optically denser than air. As the incident angle needs to be small, upscaling to large diameter solar radiation transmission systems is a challenge, in addition to the high intensities in concentrating systems.

A hollow light guide for transfer of solar radiation from a solar concentrator to a heat storage is evaluated here, by the use of a ray tracer. The ray tracer, which has been designed and programmed for application to solar reflection systems, is described and applied to cases where top-illumination of a heat storage is desired.

Light guides have been studied as means for indoor lighting technology, and commercial light tubes are available for this purpose [1-5]. Reports on light guides for high power concentrating systems have not been found in the literature. Some small wave guides are described in [6-8].

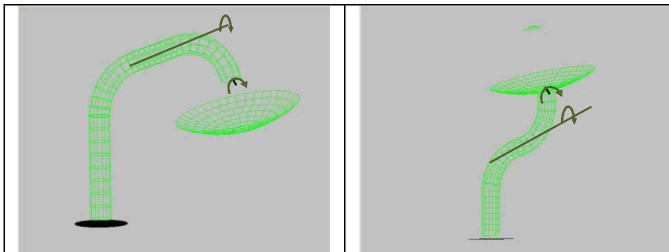
CASE

The hypothetical cases for investigation is radiation transfer from a parabolic dish which is polar mounted, see Figure 1. The daily sun tracking is by rotation of the polar axis, the seasonal change in declination is adjusted manually every few days.

With a light guide aligned with the rotational polar axis, a two-bend configuration can allow for the rotation during the sun tracking. Rigid bends can then be employed instead of flexible bends, flexible pipes with smooth internal reflecting walls are difficult to make.

Figure 1 shows the two types of cases which have been considered. The reflectors are included for illustration purposes, they are out of proportions in comparison with the light guide diameter.

The first bed is 90 degrees to the rotational polar axis, and the second bend is such that the exit pipe points vertically downwards. The angle of the second bend will then depend on the latitude of the geographical location of the system, in Ethiopia this would be about 13 degrees. The second bend to the exit pipe would then be at 103 degrees.



CASE 1 inlet at focal point

CASE 2 parallel rays from secondary reflector

Figure 1 Two cases for ray tracing analysis. Case1 has diverging rays and Case2 has parallel rays at the guide entrance. Daily sun tracking is by rotation around the polar mount light guide. Declination is by occasional adjustment around the pipe inlet.

In CASE 1 the inlet of the light guide is at the focal point of the dish, and the inlet rays will then diverge. The dish is below the rotational axis (which is the guide), so the axis will also give some shade on the reflector. For CASE 2 the inlet of the guide is below the primary absorber, and accepting rays coming from a secondary reflector. The inlet rays are then parallel. In both setups, the inlet rays will change with the seasonal declination changes (plus and minus 23.5 degrees normal to the polar axis).

The parameters of interest for ray tracing sensitivity studies are then

- Inlet ray conditions (the effect of declination changes)
- Length of the exit pipe
- Reflectivity of the internal surface

The base system for evaluation of a light guide efficiency have been chosen to be

- Diameter = 0.2 m
- Bend 1 = 90 degrees
- Bend 2 = 90 degrees + 13 degrees
- Bend radius 0.5m
- Exit pipe length: 0.5m, 1.0m, 2m
- Sun grid density = 0.0012 m grid size

The tests in CASE2, with parallel rays entering into the light guide, were made with a sun grid located at the pipe entrance. In CASE1, were the pipe inlet is positioned at the focal point of a dish with ideal reflectivity and smoothness, the following dish properties were applied:

- Dish diameter = 1.2 m
- Focal length = 0.5 m

RAY TRACER

The ray tracer has been described in [2], a short summary is given here, more in terms of the functionality than the algorithms.

The basic equations solved in a ray tracer are those to find intersections between a line and a surface and then to compute the reflected ray from the incoming ray and the surface normal vector at the intersection point.

An intersection point (P) on the surface can be reached from the ray origin point (S) by advancing u units along the unit direction vector (d) of the ray

$$\vec{P} = \vec{S} + u\vec{d} \qquad \text{(Eq.1)}$$

A surface can be described with an algebraic relation

$$p(x, y, x) = 0 \qquad \text{(Eq. 2)}$$

A surface can be a base shape as a flat plate, sphere, cylinder, paraboloid etc. A bend is implemented as a part of a toroid. Eq.1 on component form is then substituted into Eq. 2 (for the coordinates x,y,z) which gives an equation for u. With the normal vector (n) computed at the resulting intersection point (P), the reflected ray has the direction (r):

$$\vec{r} = \vec{d} + 2(\vec{d} \cdot \vec{n})\vec{n} \qquad \text{(Eq.2)}$$

The ray tracing is then management of the rays, taking also into account shading effects.

A screen shot of the ray tracer is shown in Figure 2, with an example of rays in the double reflector setup.

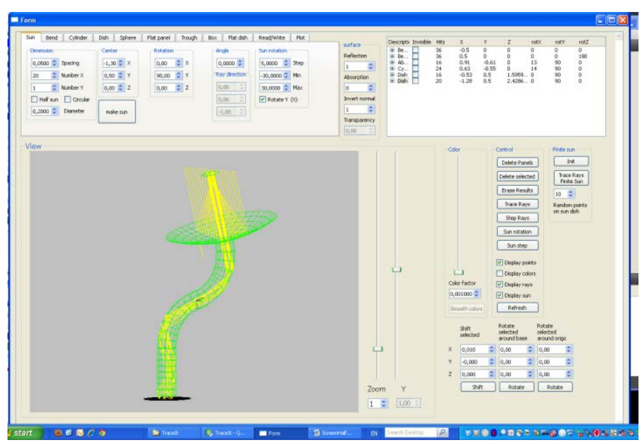


Figure 2 Screen shot of the ray tracer. Example with a double reflector system and a line array of sun points

A typical simulation sequence would be:

1) Define the sun. The sun is defined in terms of a grid of sun rays, all having the same angle. The spacing determines the resolution. This uniform grid makes the computation of interception ratios (relative number of solar rays reaching the absorber) more well defined than from a Monte Carlo method, with random sampling of initial sun rays. The shape is rectangle or spherical, with user defined position and rotation. A computational loop has also been included, where the sun angle can be varied in a series of steps, typically to investigate absorber interception factors and the tolerance for tracking errors.
2) Define panels. A panel is the base element, being either an absorber (no reflections) or a reflector (reflecting rays from one side). Some base geometries are defined (trough, dish, sphere, cylinder, cone, torus, box), and these are discretized in a user defined grid of flat squares. The user can then choose if the base geometry shall be an assembly of flat squares (e.g. many mirror tiles), or a single smooth surface (mathematical object), where the grid is then only for visualization purposes. Each assembly is given a position and a rotation. The panels appear in a 3D graphical window, where the system and the results can be inspected visually (rotation, zoom etc).
3) A model view is implemented, where the characteristics of each panel is given, as well as the hit results from the ray tracing. Selecting a panel in this model view allows for manual translation, rotation, hiding or deletion of that panel, or panel assembly.
4) After a set of absorber and reflectors are defined, the ray tracing is made. Each ray is followed from an origin, through all reflection possibilities until the ray terminates at the absorber or escapes all the system components.
5) After the ray tracing, the results can be viewed as hit points on the surface, as rays (start-stop lines) or as color codes, with a smoothing algorithm included. It can also be useful to view the generations of reflected rays as a time sequence. The results are displayed in the model view window, and can be saved in terms of sun hits for each panel, and in terms of coordinates for the sun hit points.
6) The configuration can be saved to and retrieved from file. The file is formatted, and can be edited.

RESULTS

When performing the ray tracing, the accuracy of the results will depend on the resolution of the sun grid. A sensitivity test is then useful, to determine the grid size which gives acceptable results in comparison with the asymptotic value for a very dense sun grid. Figure 3 shows a test computation which indicates that after 10000 rays the transmission factor (intensity at absorber vs. inlet intensity) does not change much. This is the value of the sun density (0.0012 grid size) which is applied in the further simulations.

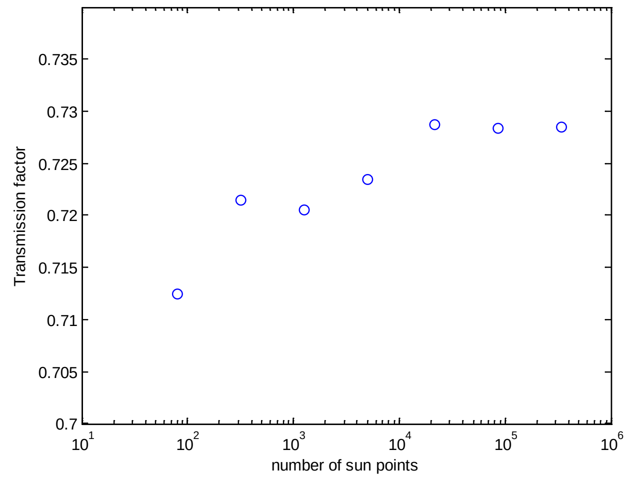


Figure 3 Sensitivity of the sun grid on the transmission factor (intensity ratio between absorber and inlet, Case 2)

The surface reflectivity will determine the losses during the transmission of rays through the guide. Figure 4 shows the transmission factor (ratio of absorber intensity to inlet intensity) for a reflectivity of 0.9 (Case 2). This is a rather low value, but not unrealistic. The results are rather weak, even for a short exit pipe about half of the inlet intensity is lost when the rays reach the absorber. No back scattering was observed, all rays entering the light guide ended on the absorber. There is some effect of the inlet ray direction (declination angle), showing higher transmission factors than for equinox conditions.

When increasing the reflectivity to 0.95, the losses are reduced, but still quite high and increasing to 40-50% losses for a 2 m long exit pipe.

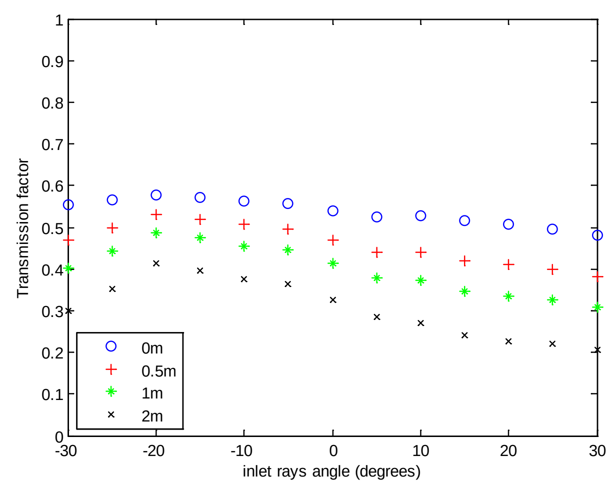


Figure 4 Case 2. Transmission factor depending on inlet ray angle (sun declination) and on length of exit pipe. Reflectivity 0.9.

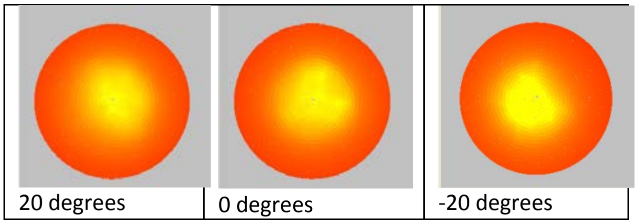


Figure 5 Intensities on the absorber for changing declination angles. Case 2.

Figure 5 indicates how the intensity distribution on the absorber changes with the declination angle. The pipe diameter is 0.2m and the absorber diameter is 0.5m. The exit rays can diverge with large exit angles, so the absorber needs to be positioned close to the exit of the light guide. Hotspots with high intensities appear to be possible.

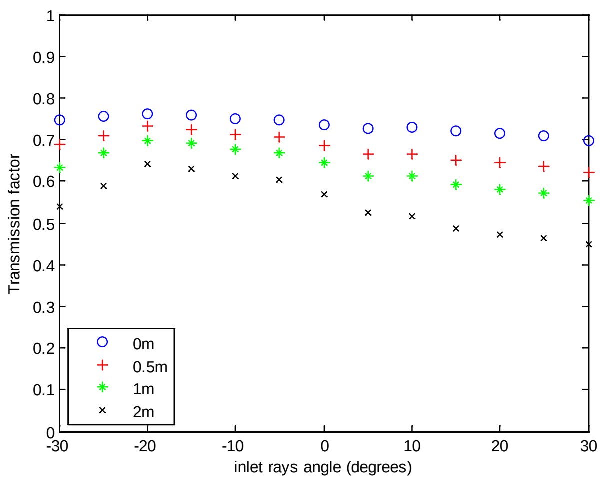


Figure 6 Case 2. Transmission factor depending on inlet ray angle (sun declination) and on length of exit pipe. Reflectivity 0.95

During the daily sun tracking the first bend will rotate relative to the second bend, which is kept stationary and pointing to a fixed absorber. The extreme case of 90 degrees rotation is compared with the vertical case in Figure 7. The differences are small, the daily rotation of the first bend does not induce many more or many fewer internal reflections.

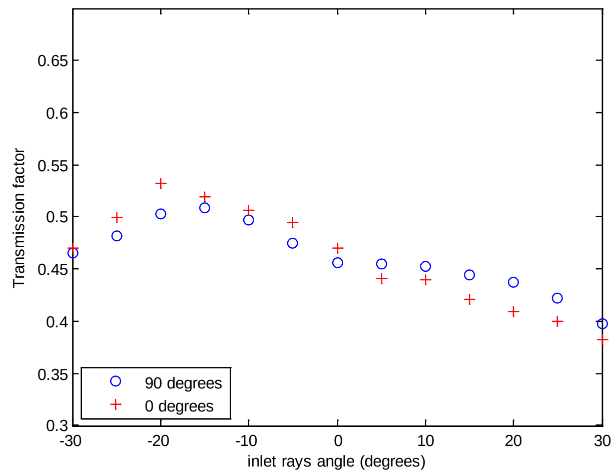


Figure 7 Case 2. Effect of first pipe rotated 90 degrees to the second pipe (largest angle for the daily sun tracking). 0.5 m exit pipe length. Reflectivity is 0.9.

One question regarding light guides is the effect of non-parallel inlet rays, as would occur if the guide inlet is positioned at the focal point of a reflector. Figure 8 shows a test case with CASE 1 where the inlet rays come from a parabolic dish instead of from a secondary dish giving parallel rays.

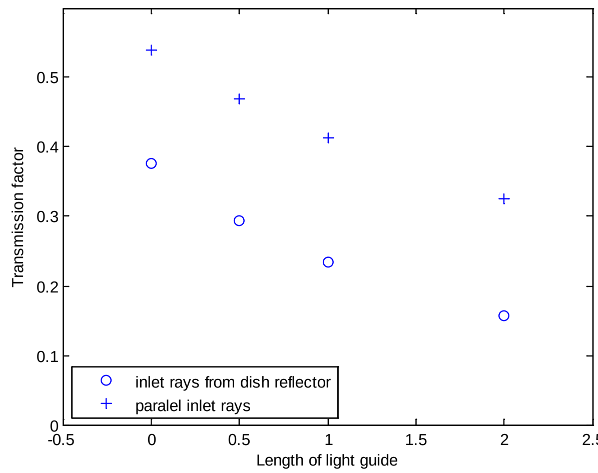


Figure 8 Transmission factor depending on pipe length. Parallel rays compared with diverging inlet rays (from a reflector). Guide reflectivity is 0.9.

The diverging inlet rays do give significantly more internal reflections, and higher losses. The results also shows that the length of a light guide will be quite limited, the intensity reduces quite rapidly as the length is increased. The inlet ray configurations are shown in Figure 9.

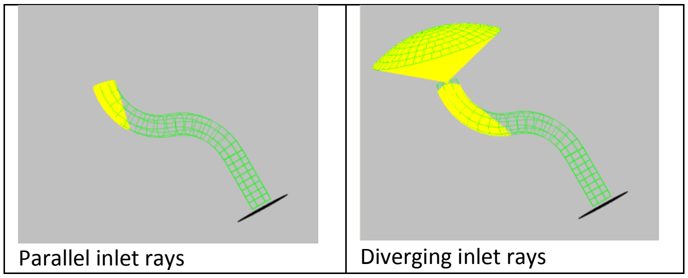


Figure 9 Inlet rays for the two comparisons

CASE 1 is a simpler setup than CASE 2, which is vulnerable to the accuracy of the secondary reflector. Strong error propagation in multiple reflector systems demands high quality surfaces and accurate reflector alignments. On the other hand, there are gains to be obtained in the transmission factor for parallel entry rays. The sensitivity to the internal reflectivity is shown in Figure 10, the transmission has a logarithmic increase with increasing reflectivity.

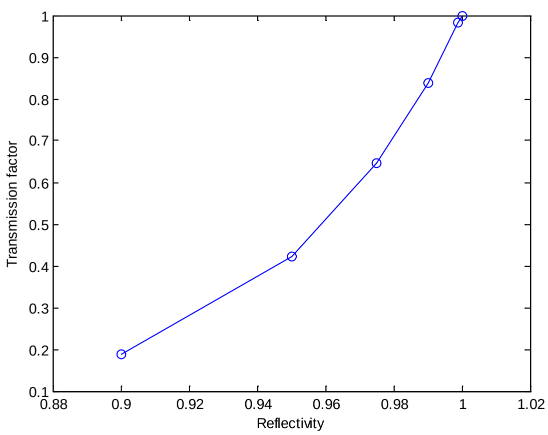


Figure 10 Transmission vs. reflectivity of a light guide. Case 2

A trial was also made with a square shaped light channel, which is easier to make using high reflective mirrors, see Figure 11. A weakness with this geometry is that the two bends cannot be rotated relative to each other, so a fixed exit location of the guide will be more difficult to achieve. What clearly disqualify the case with a squared channel are the results of the ray tracing: the transmission factor even for a short channel is 0.25, and 45% of the rays backscattered and returned back through the inlet.

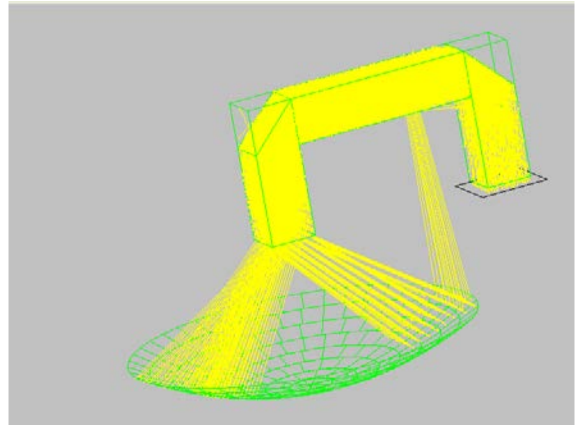


Figure 11 A square light guide showing backscatter of rays

CONCLUSION

A ray tracer has been developed for analysis of solar reflection systems. Ray tracing has been applied for evaluation of a light guide to provide the energy transfer from a solar concentrator to an absorber. The non-ideal reflectivity of the internal walls of a light guide will reduce the light intensity as the rays pass through the light guide by internal reflections. Simulations of a dual bend light guide shows that the results are not very sensitive to the inlet angle of the rays (typically 10-20% within the ± 23.5 declination angle range). The losses are lower when the inlet rays are parallel (from a double reflector system) compared with diverging inlet rays (from a focal point of a parabolic dish). The losses increases with the exit pipe length, limiting the applicability of light guides to short pipes.

A light guide could be feasible for short distances and if the internal reflectivity is higher than 0.95. Commercial light tubes for lighting purposes report reflectivity values from 0.95 to 0.99. For the dual bend case this gives about 30 % losses.

Another point of consideration is potential hot spots along the light guide. This may disqualify light guides fabricated from plastics, or other material with low temperature tolerances.

For practical applications, also involving the need for heat transport over larger distances, and the need for upscaling possibilities, it may then be difficult for a light guide system to compete in heat transfer efficiency with a heat transfer loop, where heat is absorbed at the focal point and then transported by a flowing heat transfer fluid.

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