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Ray Tracing for Evaluation of the SK14 Solar Concentrator as a Solar Fryer

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Abstract

SK14 is a well known solar dish reflector which is made for cooking in a pot positioned at the focal point. The reflector consists of aluminium sector sheets which are attached to a light frame designed for manual solar tracking. The SK14 is here evaluated as a reflector for frying of the Ethiopian injera bread. Ray tracing shows that the reflected rays spread more evenly on the pan, but also gives higher losses compared with an ideally smooth reflector. A test on heating a frying pan which was custom made for the SK14 showed that frying temperatures for injera baking can be reached with the SK14 reflector. High thermal losses and illumination of the pan at an angle results in quite long heating time for the pan.

Keywords: *Solar fryer, SK14, ray tracing, solar cooker, concentrating solar heat*

1. Introduction

The SK14 (Seifert EG-Solar 2007) is a parabolic dish, made up of sector shaped elements of reflecting aluminium. The light weight frame has a support structure for a cooking pan in the focal point of the dish. SK14 offers a low cost solution for cooking in the sun, using manual solar tracking.

Baking of the injera bread is common in Ethiopia, most often with firewood as the energy source. Electrical stoves for injera baking is available, but most households in Ethiopia are not connected to the electrical grid. As the deforestation is severe, and as Ethiopia has very good solar potentials, solar powered injera baking could be an attractive solution.

Solar baking of the injera bread has been considered earlier with direct methods (Gallagher 2011, Asfafaw et.al 2014) and with indirect methods by positioning the pan on top of a heat storage charged by steam from a solar concentrator (Asfafaw at al 2014). Systems with integrated storage units offer flexibility for the user, but tend to become more complex requiring solar tracking, heat transfer systems and storage methods.

The SK14 reflector has been designed for solar cooking. This work explores the use of SK14 for frying of injera. Ray tracing is applied for evaluation of differences between an ideal reflector and the SK14. Some tests have also been made on the heating time for an aluminium frying pan designed for the SK14.

2. Experiment

Figure 1 shows a photo of the SK14 reflector, with a cooking pot and a frying pan in the focal area. The sun tracking is made by manually turning the parabola every few minutes.

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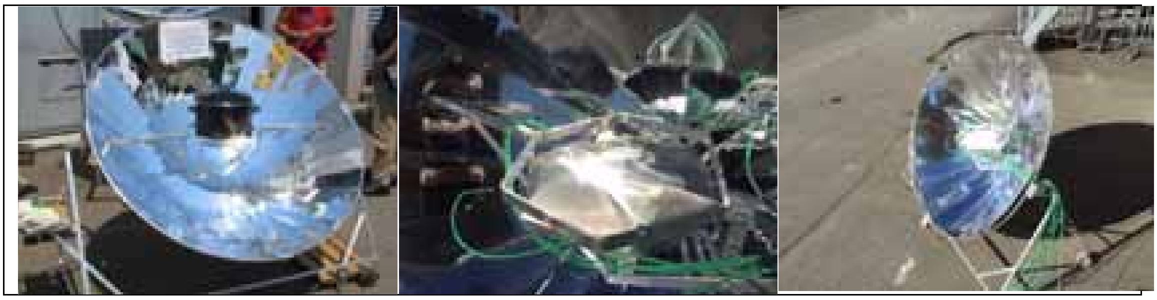

Fig. 1: SK14 with a pot and a frying pan

Two aluminum plates have been constructed (2 cm thickness each) to fit with the standard holder for the SK14 (hexagonal shape). One is anodized black, the other has no surface treatment.

A feasibility experiment was made to see if frying temperatures could be reached at non-ideal conditions, as experienced with a low solar angle in Norway (see Figure 1). Thermocouples are inserted into the plates from the side and logged during the charging of the plate in the reflector. After the baking plate is heated, the reflector is turned, giving easy access to the baking plate. The pan should have sufficient energy for 1-3 injera bakings, depending on the pan thickness.

Figure 2 shows the temperature rise of the pan in two tests. The stagnation temperatures in these tests are quite low, about 130 degrees C in the first one. The sun angle in this test was low, and midway in the first test a cold Norwegian wind started blowing, effectively halting the further temperature rise. In the second test, the response to spraying the pan with water was included. Earlier work has shown that injera can be baked on a metal surface at temperatures down to 150 degrees. Using SK14 for injera frying is therefore expected to be feasible under the more favourable conditions of the Ethiopian sun (about 13 degrees latitude).

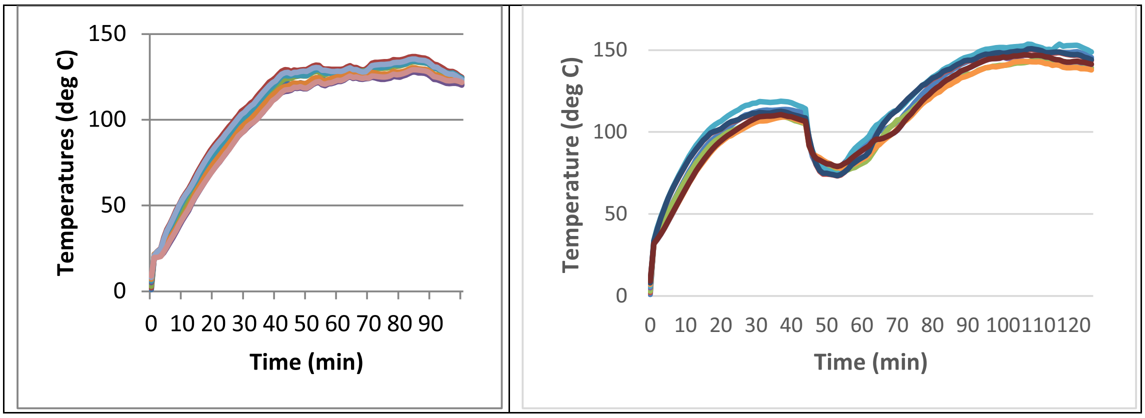

Fig. 2: Temperature rise on a hexagonal frying pan heated in the SK14 concentrator. Left: The temperature rise halted when a cold wind started blowing. Right: Water spraying of the pan after 40 minutes

3. Ray tracing

The illumination of the plates is investigated with a ray tracer, in order to optimize the position of the pan. The ray tracer is described in (Nydal, 2013, 2015). The tracer is programmed in C++, with the Qt library for the GUI and with OpenGL for the visualization. The tracer gives the user the options to assemble different kinds of reflectors and absorbers (trough, dish, plate, sphere, pipe, Scheffler reflector) for analysis with a user specified sun (density of sun points and direction). Each element can be assemblies of discretized mirror tiles or smooth mathematical surfaces. A screen shot with a 1D sun is shown in Figure 3.

The basic equation solved in a ray tracer is to find the intersectionsbetween 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 intersected point (P) on the surface is u units in length from the origin point (S) of a ray having vector (d) as the direction.

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

A surface (flat plate, sphere, cylinder, paraboloid etc.) can be described by an algebraic relation

$$p(x, y, x) = 0 \qquad (2)$$

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):

$$\vec{r} = \vec{d} - 2(\vec{d} \cdot \vec{n})\vec{n} \qquad (3)$$

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

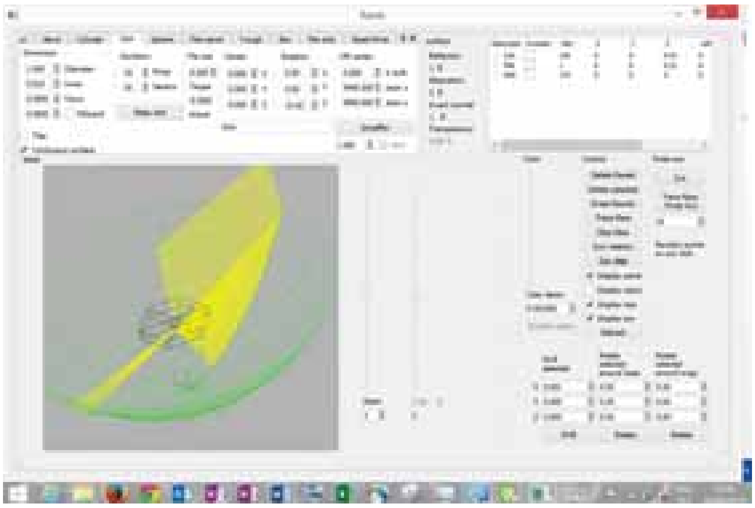

Fig. 3: Screen capture of the ray tracer program

Figure 3 shows screen captures of a case with 40 degrees sun inclination (morning or afternoon sun). The frying pan is positioned with the focal point of the concentrator at the centre point of the pan. At low solar angles, the plate will be illuminated from both sides, giving a non-symmetric heating of the plate. With an ideal reflector, all rays are captured by the plate. With a sector tiled reflector (the SK14 geometry is approximated with tiles generated from 16 sectors and 16 rings), the illumination is more spread out on the plate and the losses increases, depending on the vertical positioning of the plate (20-30% in this case).

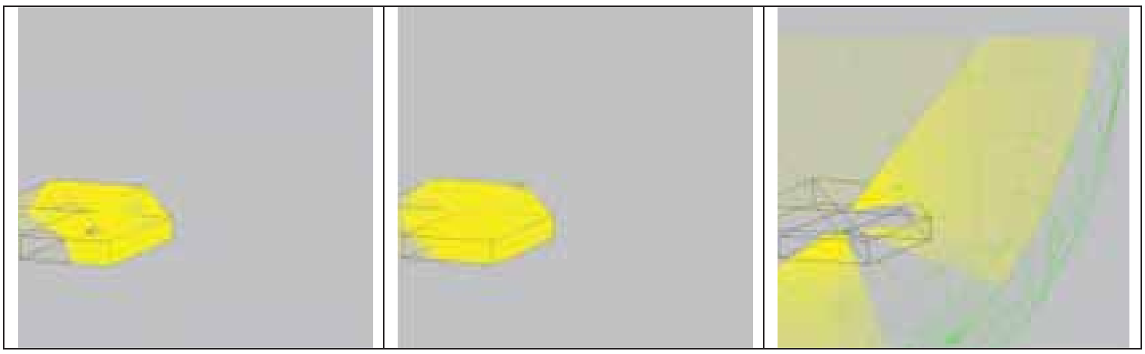

Fig. 4: Screenshots of the pan illumination at 40 degrees solar angle. Left: ideal concentrator. Centre: SK14 concentrator. Right: Test with a 1 dimensional sun (sun rays on a line)

Figures 5 and 6 show sensitivities to the vertical positioning of the pan by adjusting the height such that the focal point is at the bottom, centre and top of the pan. The simulations are made with a sun covering half of the concentrator.

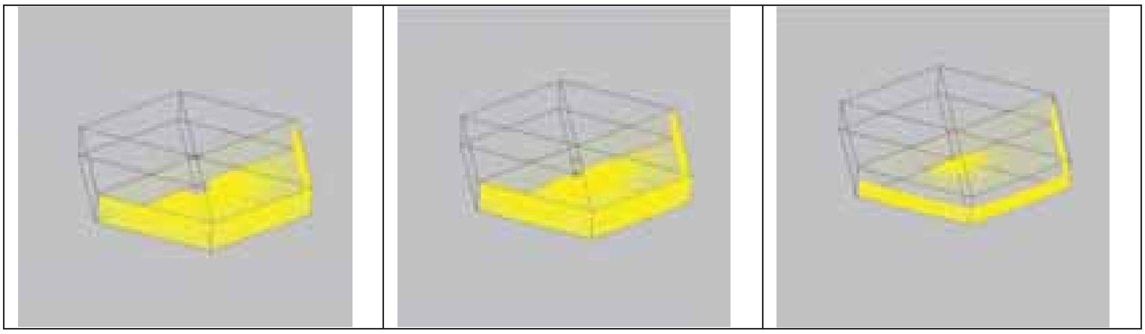

Fig. 5: Screenshots of the pan illumination at different vertical positions. Smooth concentrator, half illuminated
Left: Focal point on top. Centre: focal point in the centre of the pan. Right: focal point at the bottom

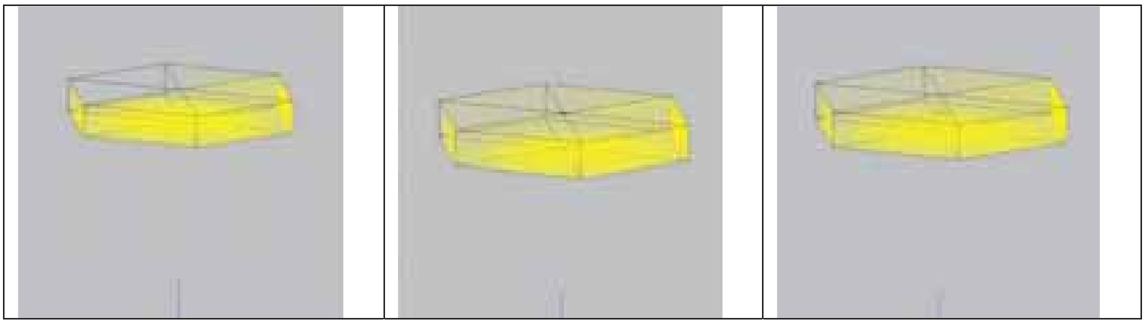

Fig. 6: Screenshots of the pan illumination at different vertical positions. SK14 concentrator, half illuminated
Left: Focal point on top. Centre: focal point in the centre of the pan. Right: focal point at the bottom

The SK14 concentrator spreads the reflected rays significantly more than the ideal smooth reflector. This gives less sensitivity to the positioning of the pan, but does also give higher losses. The ideal reflector shows a more critical sensitivity to the positioning of the pan, with also a higher risk of generating hot spots on the pan.

4. Discussion

Figure 7 shows the temperature time recordings of Figure 2 plotted with a time shift to allow for comparisons of trends. The temperature measurements in Figure 2 do show some variations for the different thermocouples. The illumination is not uniform across the plate, nor at the different sides of the plate. Figure 7 includes the band of the measurements.

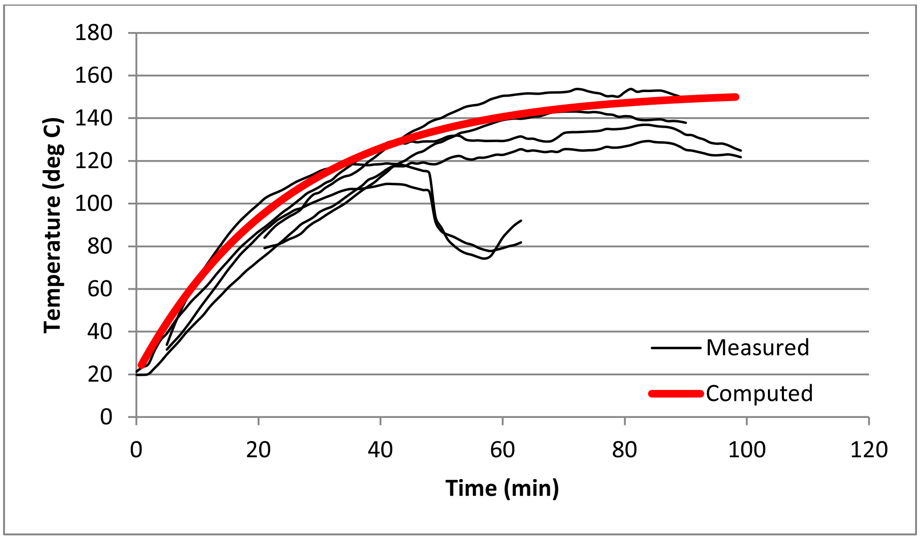

Fig. 7: Overlapped temperature measurements from Figure 2 (thin lines) and computational estimates (thick line)

A simple computational estimate can be made by neglecting the internal heat transfer dynamics (heat conduction) and consider the pan to have uniform temperature. The temperature evolution can then be computed from estimates of the solar radiation and of the losses. Figure 7 shows the integrated temperature from the energy balance:

$$\frac{\partial \rho A d c T}{\partial x} = \rho C_r A - h A_i (T - T_a) \qquad (4)$$

The definition of the variables and the numbers which have been applied are given in Table 1.

Table 1 Values for the temperature computations

Variable	Value	Comments
ρ - density	2800 kg/m^3	The temperature dependency is neglected
A - plate area	0.0706 m^2	The plate is hexagonal, but the area is for simplicity estimated from a circle with a diameter of 30 cm
A_l- area for heat losses	2A m^2	The plate is hexagonal, but the loss area is for simplicity estimated from the top and bottom surfaces, sides neglected
d - plate thickness	0.02 m	
c - heat capacity	910 J/KgK	The temperature dependency is neglected
T - temperature		
h - heat transfer coefficient	9 W/m^{2}K	This value is tuned based on the experiments
T_a - ambient temperature	20 degrees C	
q - solar radiation	900 W/m^2	This is a typical value measured in Trondheim on a clear and sunny day. The solar intensity was not measured at the day of the experiments, so the value is an estimate
C_r- effective concentration ratio	5	This value is tuned based on the experiments, and includes all optical losses

From Figure 7 it can be seen that the uncertainty in the heating and loss conditions of the plate in the SK14 concentrator can be quite large. The solar tracking is manual and the ambient conditions can change during the heating – wind has a strong effect on the heat losses from the plate. This rough estimate, based on tuning of the heat supply (the effective concentration ratio) and the losses (the effective heat transfer coefficient for the top and bottom surfaces) indicates that the stagnation temperature will in this Norwegian case be quite low. Frying temperatures can be reached, but after considerable time.

If one side of the pan could be insulated, the losses could potentially be reduced. Figure 8 shows ray tracer results for two latitude cases: Trondheim in Norway (about 60 degrees) and Mekelle in Ethiopia (about 13 degrees).

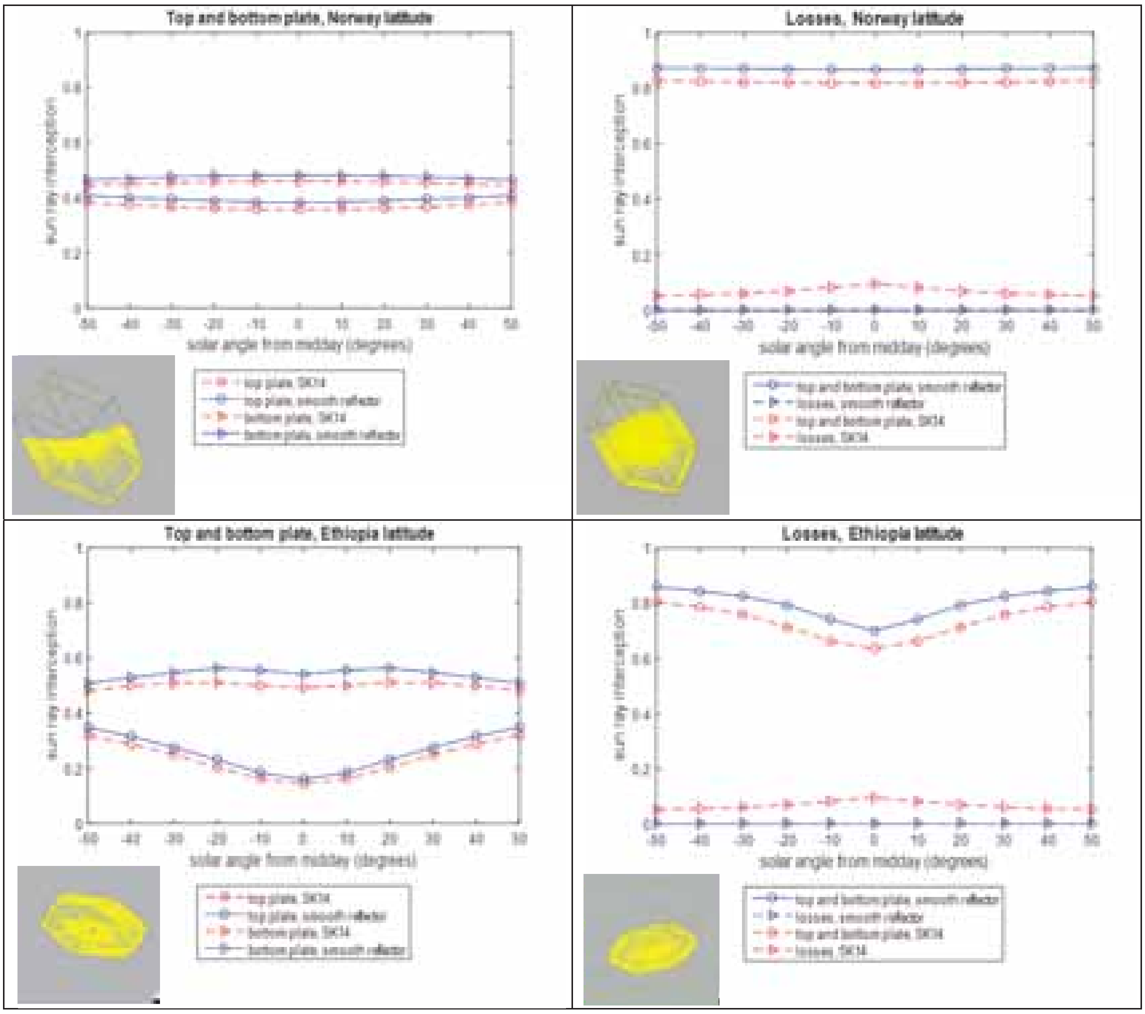

Fig. 8 Ray tracing results for solar tracking during a day in Norway and in Ethiopia

With the frying pan kept in a horizontal position the angle with the concentrator will be larger in Norway than in Ethiopia. This means that both sides of the pan will be illuminated more in the Norwegian case than in the Ethiopian case. Insulating the top plate during heating of the plate may not provide a strong benefit even for the Ethiopian case, as the top illumination is still quite large also at Ethiopian latitudes. The illumination of the sides of the plate is also significant (about 10%).

5. Conclusions

From previous tests, it has been demonstrated that the Ethiopian injera bread can be baked on an aluminium surface. The tests made in this work shows that frying temperatures can be reached in an SK14 concentrator, fitted with a custom made aluminium pan. The SK14 can then be a low cost alternative for direct solar injera baking.

The pan is exposed to the ambient, so the thermal losses will reduce the performance of the fryer. The sector tiled geometry of the SK14 spreads the reflected sun rays more on the pan, but also gives higher losses due to rays missing the pan, compared with an ideal concentrator. An ideal reflector surface can, however, give a too concentrated illumination of the pan depending on the positioning in relation to the focal point.

The direct frying system can be optimized by using a concentrator with a smaller rim angle. If only one side of the pan is illuminated, it can open for insulation of the other side, and similarly during frying.

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