OPTICAL SIMULATION OF A 10 kW_{el} DISH/STIRLING UNIT USING RAY-TRACING CODE SOLTRACE

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Abstract

This paper presents optical simulations of 10 kW_{el} Eurodish Dish/Stirling unit erected at the CNRS-PROMES laboratory in Odeillo in FRANCE. The global thermal model of the energy conversion, SIM_ED_PROMES, developed by PROMES laboratory has shown that the main heat losses are situated in the optical system package (parabolic concentrator, solar receiver).

To increase the net solar-to-electrical efficiency, it is essential to know the optical performances of the subsystem formed by the solar receiver and the parabolic concentrator. In 2005, the “color-coded targets” method developed by the DLR was used to measure slope errors of the parabolic concentrator. The high spatial resolution of this method is used to simulate the concentrator behaviour using the ray-tracing code SOLTRACE developed by the NREL laboratory. In order to verify the concentrator model, the solar flux distributions calculated by SOLTRACE are compared to flux measurements close to the focal plane. The comparison shows a good agreement especially in the shape of the flux map in the absorber plane.

Currently, the laboratory uses SOLTRACE to estimate flux distributions for different receivers. Flux maps are introduced in the thermal model SIM_ED_PROMES to calculate the absorber temperature levels, the heat losses, the receiver efficiency and the Stirling engine efficiency.

Keywords: solar thermal electricity, Stirling engine, parabolic dish, ray-tracing simulation, thermal model, SOLTRACE.

1 Introduction

Since July 2004, a 10 kW_{el} Dish/Stirling unit is in operation at the PROMES Laboratory. This system is one of the several Country Reference Units of the Envirodish project. It is a Eurodish system developed by DLR and SBP for solar electricity generation using a Stirling engine externally heated by concentrated solar radiation[1]. During these two years, the system has accumulated 3000 operation hours and more than 15 MWh_{el} of electricity production with a power record of 11.1 kW_{el} at 974 W/m² direct normal insolation (DNI), which corresponds to a net solar-to-electrical efficiency of 21.6 %.

The global thermal model of the energy conversion called SIM_ED_PROMES and developed by the PROMES laboratory has shown that the main heat losses are situated in the optical system package (parabolic concentrator, solar receiver). The optical efficiency representing the ratio of the thermal power introduced into the Stirling engine to the solar power intercepted by the concentrator, is estimated by the SIM_ED_PROMES model at 64 %.

Two mains categories of codes for solar flux calculation can be distinguished[2]: Codes like MIRVAL, FIATLUX and SOLTRACE are designed to detailed analysis of the optical performances and give a detailed description of the reflected power from a concentrator. The second category of codes (UHC, DELSOL, HFLCAL) is dedicated to global system optimization. In order to develop a new receiver design, the first category of code is necessary. The ray-tracing code SOLTRACE, developed by the NREL laboratory is ideal to study performances of optical components of a Dish/Stirling system. It is in the public domain, runs in Windows environment on standard computers with user-friendly graphic interfaces (flux maps and 3D visualization) and is adapted to the three main technologies of concentrated solar power plants (Central Receiver System, Parabolic Trough and Dish/Stirling),

The solar flux distribution on the absorber is a key parameter of the Dish/Stirling system. Flux peaks on the absorber induce temperature gradients decreasing the Stirling engine efficiency. To know these flux peaks, it’s necessary to introduce in the ray-tracing code the local slope errors and not the total concentrator error.

Currently, three methods have been developed to measure the local slope errors of a concentrator: The first one, photogrammetry is used to measure with a high precision the 3D coordinates of the concentrator from a network of multiple photographs[3]. The VSHOT measurement system developed by SANDIA is based on the reflection of a laser beam[4]. The last one is the "color-coded targets" method developed by DLR[5].

1 *Slope errors of the Eurodish unit in Odeillo*

The parabolic dish of the Eurodish system has a diameter of 8.5 m. It consists of a thin shell, composed of 12 segments in V glass-fiber-reinforced resin sandwich with the mirrors applied to its surface. The ideal shape of the concentrator is 10 rings of parabola with slightly different focal lengths defined by Eq.1. The design value of the focal length of the whole parabola is 4.52 m. When the concentrator is cleaned, its reflectivity is measured at 92.5% and its effective area considering shadings is about 53 m².

$$Z = A_n (X^2 + Y^2) + B_n \qquad \text{(Eq.1)}$$

Where A_n in m^{-1} and B_n in m are two coefficients characterizing each parabola ring n.

The "color coded target" method developed by DLR was tested and validated for DISTAL-2 and Eurodish Dish/Stirling systems[5]. This method is based on the measurement principle called deflectometry which consists to observe the reflection of a regular pattern on a mirror surface. In the area of SOLFACE program, in 2005, a DLR team was used this method to characterize the parabolic concentrator of the Eurodish unit in Odeillo.

Figure 1 gives the slope errors in radial and tangential direction compared to Eurodish concentrator design (10 rings of parabola). It can be seen white areas representing the missing data. Only 37,9 m² could be evaluated which represents 71 % of the total concentrator area. The figure 1, on the left, shows the slope errors in radial direction. The whole concentrator has slightly negative slope errors in the radial direction, which mean a too long focal length. Two notable rings, one at a radius of about 2.50 m with positive slope errors and one at 3.50 m with negative slope errors can be observed. Two segments differ from the others: the first one at one o'clock position has a larger positive slope error and the second one at 5 o'clock has a larger negative slope error. The figure 1, on the right, representing the slope errors in tangential direction shows a repeating pattern in almost all the segments. For each segment, there are mainly negative slope errors in one half and mainly positive slope errors in the other half.

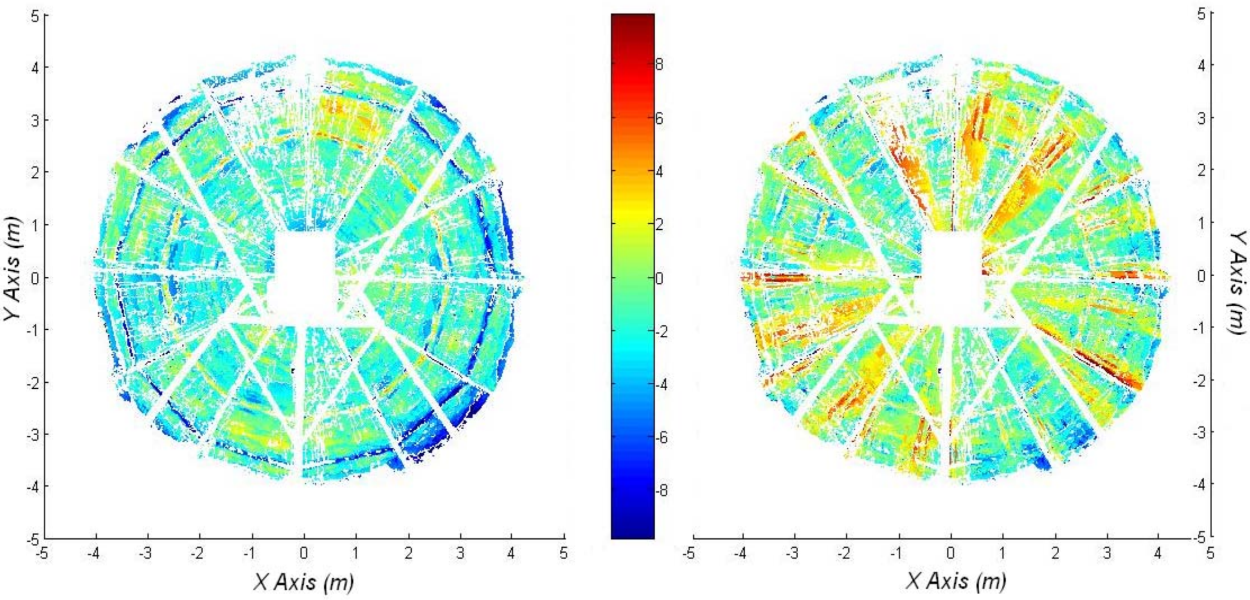

Figure 1. Slope errors in mRad (compared to the design concentrator) of the Eurodish concentrator in Odeillo. Left: Slope errors in radial direction (>0: inward deviation). Right: Slope errors in tangential direction (>0: clockwise direction)

2 Parabolic concentrator model in SOLTRACE

2.1 The ray-tracing code SOLTRACE

The objective of SOLTRACE is to model complex optical systems for solar power and to analyse their performance. The optical system is organized in stages in a global coordinates system: stages are sections of the optical geometry that are successively hit by rays in their pathway from the sun to the final receiver. They can be optical ones (physical interactions with rays) or virtual ones (useful to determine flux maps). One stage is composed by elements with their own properties. Each element is described in a coordinates system related to its stage. The complete description of geometry of the elements leads to a cumbersome interface. Indeed for each system, all the optical geometry must be built in a spreadsheet including:

-Definition of each element: coordinates, aperture type, surface type, normal direction, optical properties

-Definition of each stage coordinates system in relation to the global coordinates system.

This organization implies the calculation of the position of each element of the optical system depending on the sun position[2].

2.2 Parabolic concentrator model

Several methods can be used to model a parabolic concentrator in SOLTRACE:

-The easiest is to define the whole parabolic dish with an 8.5 m diameter and a 4.52 m focal length. In this way, only a total slope error can be defined.

-A second method is to define the 10 parabolic rings of the Eurodish concentrator using Eq.1. This can be the best way to model the ideal shape of the Eurodish concentrator. Furthermore, we can attribute a total slope error for each parabolic ring.

-The method that we use consists to divide the parabola in small elements and then, to apply at each element a normal vector depending of the local slope error.

The problem of this method is that to simulate correctly the parabolic dish, one element should correspond to one slope error measurement. The resolution of the "color coded target" is an 11.348 mm per 11.348 mm area, which represents more of 400000 slope errors measurements. Unfortunately SOLTRACE is limited to 6000 elements. To get round this problem, the idea is to divide the parabolic dish in 4421 parabolic square facets of 11.348 cm per 11.348 cm corresponding to a matrix of 10*10 slope errors measurements.

In order to validate this methodology, we compare SOLTRACE results of the ideal shape defined by 10 parabolic rings divided in 4421 parabolic square facets with the ideal shape defined by 10 parabolic rings. Each facet *F* is oriented using an ideal normal vector $\underline{n}_{\text{ideal}}$ calculated from the ideal shape. The facet coordinates (X_0, Y_0, Z_0) and the ideal normal vector coordinates are:

$$F\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 = A_n(X_0^2+Y_0^2)+B_n \end{pmatrix} \quad \text{and} \quad \underline{n}_{ideal}\begin{pmatrix} -X_0 \\ -Y_0 \\ \dfrac{1}{2B_n} \end{pmatrix} \qquad \text{(Eq.2)}$$

Moreover, each facet is parabolic and the focal length given by Eq.3 is equal to the distance between the parabolic dish focal length and the facet localization:

$$f_F = \sqrt{(X_0^2+Y_0^2+(f_{CONC}-Z_0)^2)} \qquad \text{(Eq.3)}$$

Figure 2 shows the diagrams of peak flux and solar energy intercepted by an aperture of 19 cm diameter depending on the distance to the focal plane (4.52 m). Values are given for a concentrator reflectivity of 94 % and a DNI of 1 kW/m². The parabola model using 4421 ideal parabolic square facets gives the same results than the ideal shape with differences less than 5% for the flux peak and less than 1% for the intercepted solar energy.

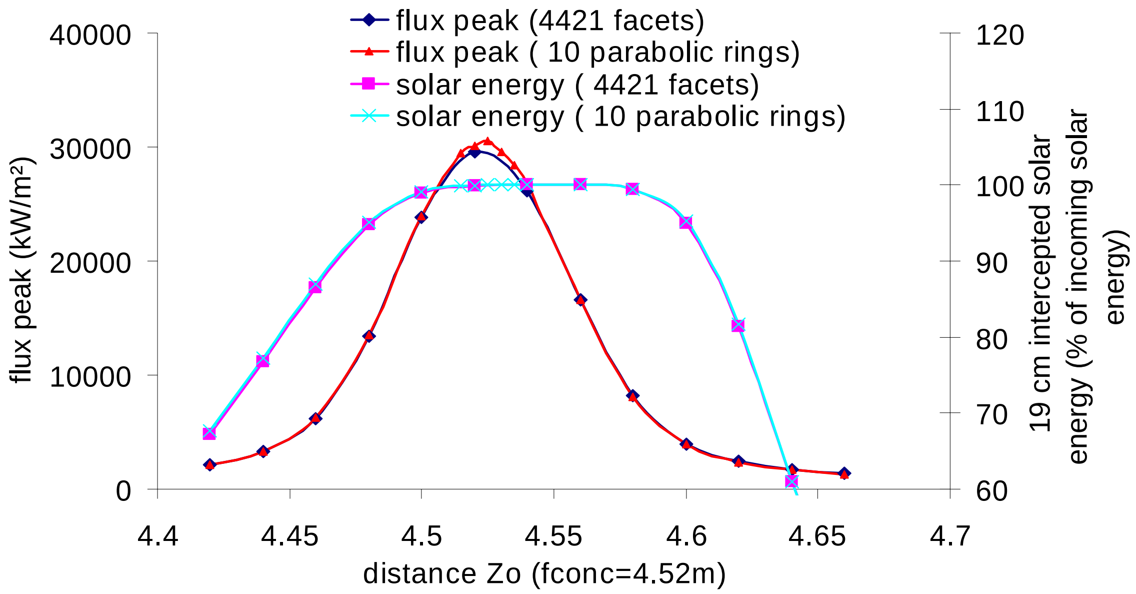

Figure 2. SOLTRACE results for two models: Ideal shape of Eurodish dish (10 parabolic rings and 10 parabolic rings divided in 4421 parabolic facets)

2.3 comparison SOLTRACE results-flux measurements

Having validated the methodology, the local slope errors matrix can be introduced in SOLTRACE. For each facet, an algorithm developed in Matlab calculates a "mean" normal vector $\underline{n}_{real}$ (figure 3) given by Eq.4 from matrix of 10*10 slope errors measurements ignoring the missing data. Then, values are exported to SOLTRACE for simulations.

$$\underline{n}_{real,F} = \frac{1}{j}\sum_{i=1}^{j}\underline{n}_{real,El} \qquad \text{(Eq.4)}$$

Where the normal vector $\underline{n}_{real,El}$ is deducted from slope errors measurements in x and y directions (figure 3).

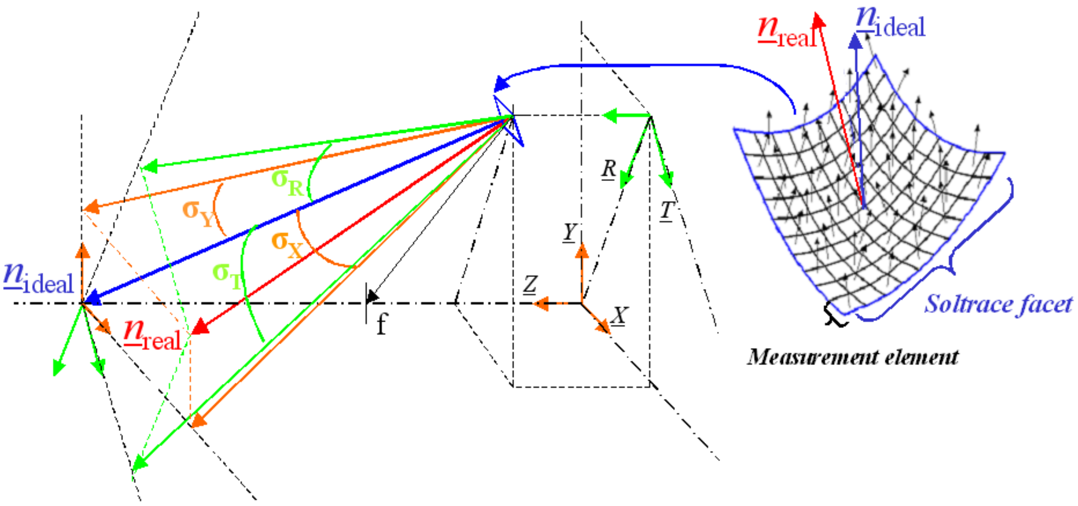

Figure 3. Slope errors in X, Y, Radial and Tangential direction

To be in the Eurodish operation conditions, shadows due to Stirling unit and concentrator structure are introduced in the model blocking certain rays incoming from the sun. Furthermore the Gaussian sunshape defined by SOLTRACE is used. Figure 4 shows the parabola geometry in SOLTRACE with traced rays.

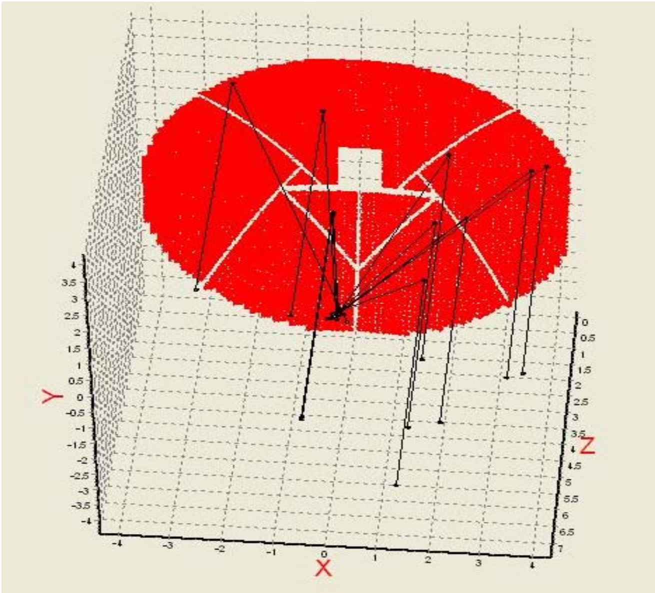

Figure 4. Parabola geometry in SOLTRACE

To verify the quality of results, the flux distributions calculated by SOLTRACE are compared to flux maps measurements made by DLR team in 2005 in two planes[6]. The first one corresponds to the aperture plane of the Eurodish receiver located at the measured focal plane Z=4.553 m (design value at 4.52 m) and the second one is the absorber plane, 12 cm behind the aperture plane.

Figure 5 shows SOLTRACE results and measurements normalized to a concentrator reflectivity of 94 % and a DNI of 1 KW/m². The simulated overall size is good. The solar energy intercepting by an aperture of 19 cm is estimated to be 88 % of the reflected solar energy instead of 85 %, which gives a difference of 1.5 kW. The major difference is between the calculated peak flux (7650 kW/m²) and the measured value (9300 kW/m²). In additional to the uncertainties in simulation and measurements, these differences can be explained by the missing data in the slope errors matrix.

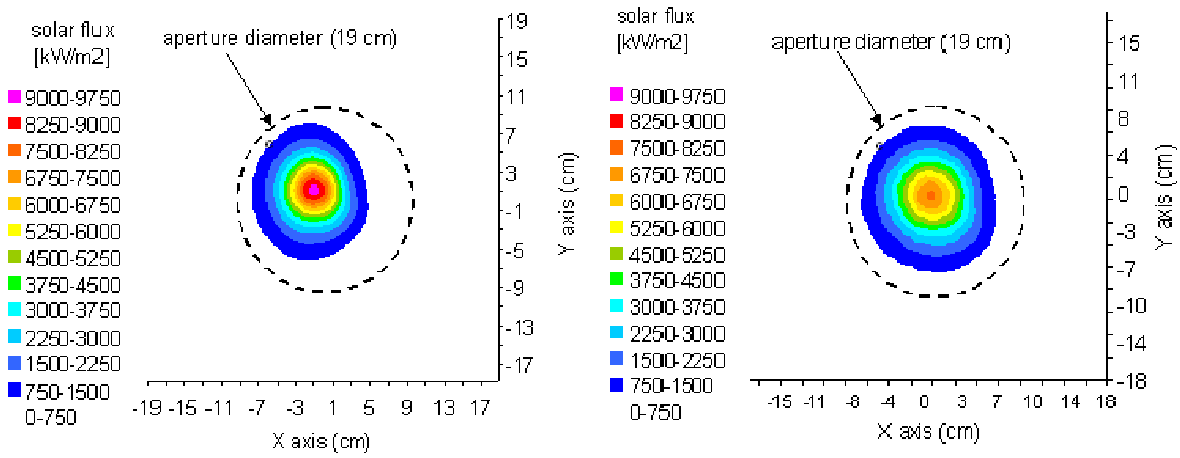

Figure 5. Solar flux distribution in the aperture plane (Z=4.553 m). Left: Measurements[3]. Right: SOLTRACE

In the absorber plane (figure 6), the rays diverge and the irregularities in the solar flux distribution due to local slope errors of the concentrator become more evident. The shape of the flux map in the absorber plane is well estimated. It shows the same peak but with a higher value in the upper part and the minor peak in the right part. The flux peak is calculated at 1800 kW/m² instead of 1583 kW/m². Solar energy intercepted by the hexagonal absorber is estimated at 83 % of the reflected solar energy and is measured at 78 %.

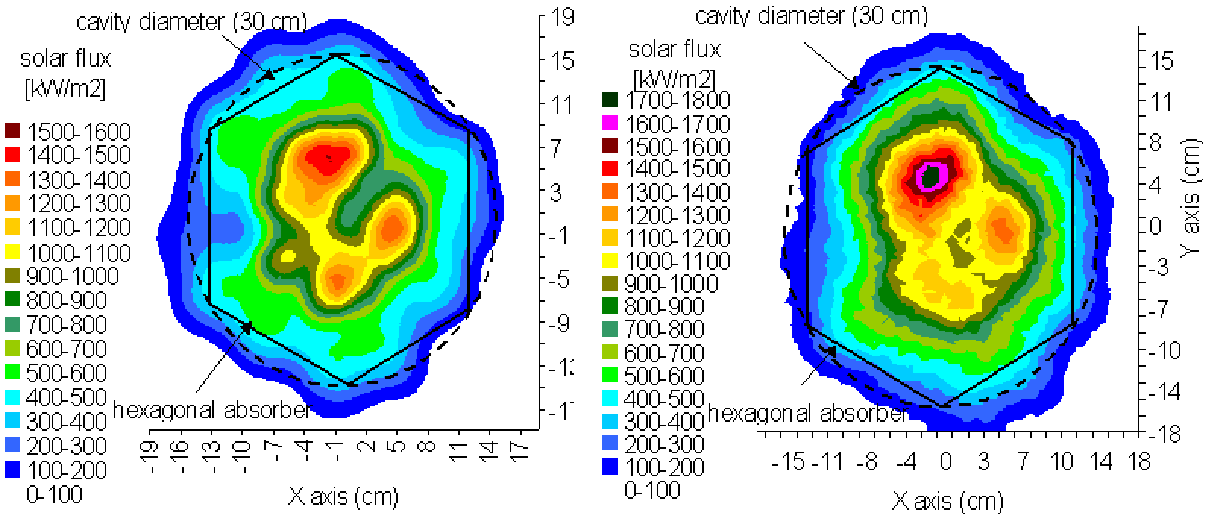

Figure 6. Solar flux distribution in the absorber plane (Z=4.673 m). Left: Measurements[3]. Right: SOLTRACE

3 SIM_ED_PROMES thermal model

The thermal model "SIM_ED_PROMES" is composed of a radiation transfer model for the cavity and of a thermodynamic model for the Stirling engine. The solar receiver is composed of a ceramic cylindrical cavity of 30 cm in diameter and 12 cm in depth; the concentrated solar radiation enters through an aperture of 19 cm in diameter. The hexagonal absorber composed of 78 tubes made of Inconel of 3 mm outer diameter is placed at the bottom of the cavity. A nodal method is used to calculate the heat losses by reflection, by IR emission, by convection out of the cavity, and by conduction trough the insulating ceramic. The energy provided to the working gas flowing in the absorber tubes is also calculated over one complete cycle of the Stirling engine. The receiver is divided into 11 control-volumes: 8 for the absorber, 2 for the irradiated and shadowed cavity walls and 1 for the aperture. Each insolated control-volume is assumed to receive a uniform solar flux density estimated from SOLTRACE results. Then a nodal method is used to simulate one Stirling engine cycle, yielding the estimation of the generated mechanical power and the electrical power.

In a first time, results of SIM_ED_PROMES are compared to experimental results presented by Reinalter et al[6]. The Eurodish operation data during the experimental measurements are provided in table 1.

working gas	hydrogen	
DNI	W/m²	906
Concentrator area	m²	52.9
Concentrator reflectivity	%	92.5
Maximal absorber temperature	K	1053
T_{am}	K	283
Speed stirling engine	$rt.min^{-1}$	1500

Table 1: Eurodish operation data

Table 2 give the mean solar flux for each "absorber" control-volume calculated from the measured flux map in the absorber plane (figure 6 on the left). The mean solar flux on the absorber is measured at 702 kW/m². The highest solar flux is located on the "absorber" control-volumes 4 and 5 and is equal to 152 % of the mean value and the lowest is located on the control-volume 3 and is of 57 % of the mean value.

Control-volume		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Absorber*
Mean Solar Flux	kW/m²	0	501	403	1052	1068	569	521	0	702

Table 2: Measured mean solar flux for each "absorber" control-volume

Figure 7 gives the SIM_ED_PROMES results and the experimental measurements of the solar energy dispatching. This figure shows the considerable energy losses in the receiver in particular by spillage.
The developed model gives good results in agreement with the measurements particularly in the receiver. The efficiency of the cavity/receiver defined as the proportion of the thermal energy introduced into the engine to the

power that enters in the cavity is estimated at 81.4 % and is measured at 82.6 %. The observed differences between the model results and the measurements are due to the Stirling model The Stirling engine efficiency which represents the conversion of thermal to mechanical power is calculated at 34.4 % and is measured at 39.2 %. Finally, the Eurodish efficiency is evaluated at 19.1 % instead of 22.5 %.

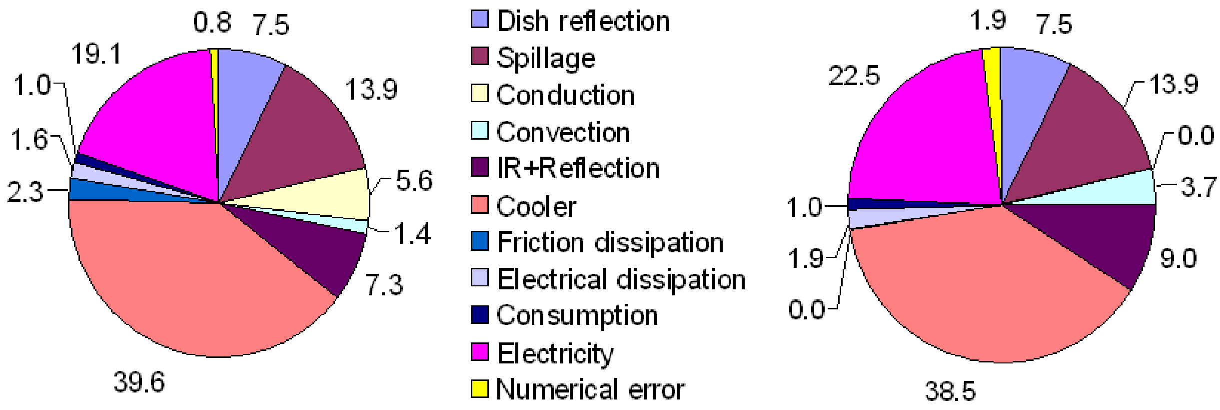

Figure 7: Solar energy dispatching: Left: SIM_ED_PROMES, Right: Reinalter et al.[6]

Figure 8 shows the absorber temperature distribution calculated by the model and measured by 20 thermocouples placed behind the absorber. It can be seen a good agreement between the model results and the measurements. The difference between the maximum and minimum temperature is calculated at 130 K when measurements gives about 100K

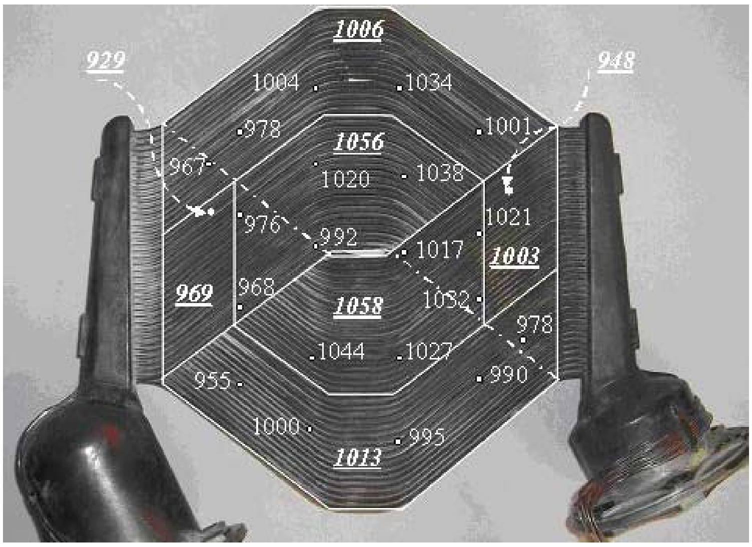

Figure 8: Absorber temperature distribution: model results (underlined)

The SIM_ED_PROMES model compared to experimental measurements gives good results and permits to study the detailed heat losses in particular in the receiver.

4 Optimization of Eurodish cavity geometry using SOLTRACE and SIM_ED_PROMES

The principal advantage of ray-tracing simulation is that a geometry receiver can be added in the model. Using SOLTRACE and the SIM_ED_PROMES model, the influence of the cavity geometric parameters can be evaluated and optimized.

Figure 9 shows the evolution of the components efficiencies as a function of the aperture diameter. The Eurodish efficiency is constant at 19.6 % for a aperture diameter higher than 19 cm and it decreases to 14 % for a 10 cm diameter. The concentrator efficiency, defined as the proportion of energy entering in the cavity to solar energy intercepted by the dish, increases with the aperture size; spillage losses pass from 4.6 kW at a 19 cm diameter to 1.5 kW at a 30 cm diameter but are compensated for cavity losses (conduction, convection, IR emission, reflection). Stirling engine efficiency increases slightly from 33.5 % at 30 cm diameter to 34.8 % at 10 cm diameter because the flux distribution on the absorber becomes more homogeneous. Finally according to the model, a diaphragm is not necessary for a cavity of 12 cm in depth and 30 cm in diameter.

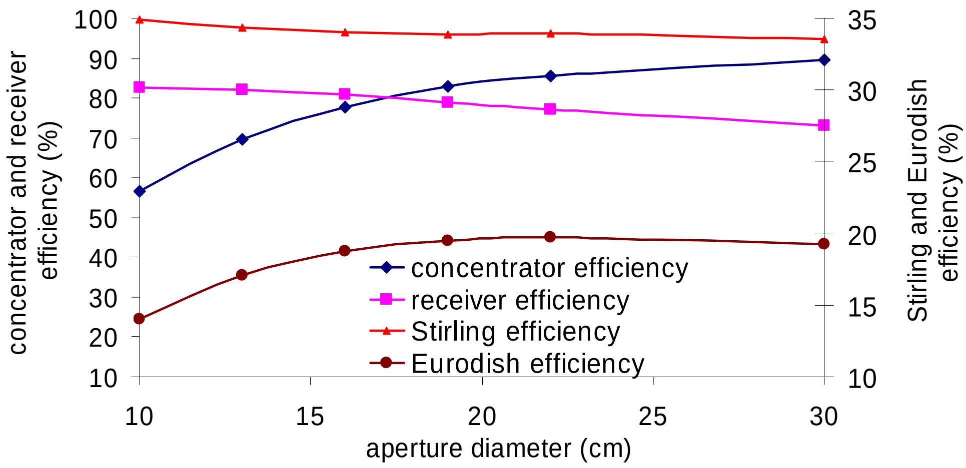

Figure 9. Evolution of Eurodish components efficiencies as a function of the aperture diameter

Conclusion

This paper presents optical simulations of the Eurodish unit using the ray-tracing code SOLTRACE. From slope errors measurements, a concentrator model is built and simulation results are compared to flux maps measurements close to the focal plane. The comparison shows a pretty good agreement in particular for the flux map shape in the absorber plane. A receiver model is added in the ray-tracing simulations in order to study the influence of cavity physical parameters. Spillage losses and flux distribution in the receiver estimated by SOLTRACE are introduced in the thermal model SIM_ED_PROMES to calculate the absorber temperature levels, the heat losses, and the components efficiencies. Results show that a diaphragm is not necessary for a cavity of 12 cm in depth and 30 cm in diameter. Currently a kaleidoscope-type cavity is tested using SOLTRACE. This type of cavity allows to obtain an homogeneous solar flux distribution on the absorber and to increase the Stirling efficiency.

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