

Optical Analysis of Variable Aperture Mechanism for a Solar Reactor

Akanksha Menon, and Nesrin Ozalp

Abstract—Solar energy is not only sustainable but also a clean alternative to be used as source of high temperature heat for many processes and power generation. However, the major drawback of solar energy is its transient nature. Especially in solar thermochemical processing, it is crucial to maintain constant or semi-constant temperatures inside the solar reactor. In our laboratory, we have developed a mechanism allowing us to achieve semi-constant temperature inside the solar reactor. In this paper, we introduce the concept along with some updated designs and provide the optical analysis of the concept under various incoming flux.

Keywords—Aperture, Solar reactor, Optical analysis, Solar thermal

I. INTRODUCTION

SOLAR thermal processing provides many products with zero or near to zero emissions. Therefore it attracts researchers to develop solar thermal reactors that can house these thermochemical processes to manufacture various solar fuels and commodities [1, 2]. However, most of the solar thermochemical processes require high temperatures at above 1000°C for the reaction to reach equilibrium, thus temperature plays a key role in production efficiency. In order to obtain such high temperatures, incoming solar energy is concentrated towards the focal point of solar thermal reactors. Due to changes in weather conditions, incoming solar flux varies throughout the day. That makes an undesired impact on feedstock to product efficiency because of changes in temperature inside the solar reactor.

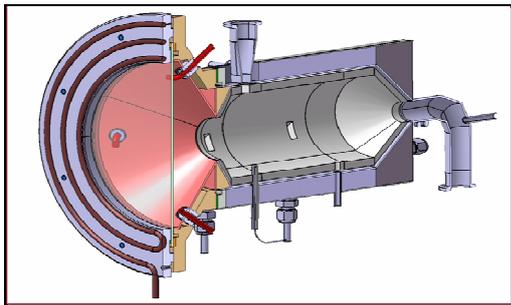


Fig. 1 An example solar reactor [3]

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A solar reactor is mainly composed of (1) a cavity, where the chemical reactions take place, (2) an aperture, where the concentrated solar energy enters the cavity, (3) inlet and outlet ports for the feedstock and the products. An example solar reactor is shown in Fig. 1 [3]. Solar reactor designs in literature involve fixed aperture concept. When the incoming solar flux changes due to the changes in weather conditions, such as passing clouds, fixed aperture concept does not compensate variation in solar flux amount. This results with a drop in solar reactor temperature.

At our laboratory, we have developed a mechanism that can adjust itself against the changes in weather conditions [4-6]. With this new mechanism, called “camera-like aperture”, the heat loss due to weather changes can be substantially minimized. Camera-like aperture mechanism is sensitive to the continuous changes in solar flux. It adjust itself by reducing its diameter when the solar flux is low, and by increasing it when the solar flux is sufficiently high in order to maintain semi-constant internal temperatures.

In this paper, we provide optical analysis of this new mechanism using Monte-Carlo ray tracing method. We present the optimum aperture diameter based on compromise between useful power obtained and radiation losses incurred.

II. VARIABLE APERTURE CONCEPT

Variable apertures are used in photography, spectrometry and high energy radiation applications [7-11]. A comparison of these variable aperture concepts is shown in Table 1. In our previous studies, we initially developed a simple variable aperture mechanism consisting of two blades as shown in Fig. 2, and implemented a dynamics and controls mechanism [4].



Fig. 2 Our initial variable aperture design [4]

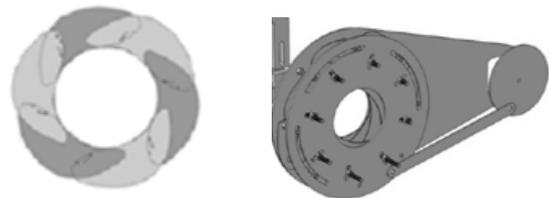
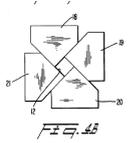
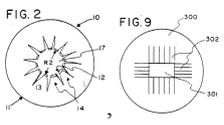
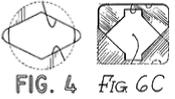
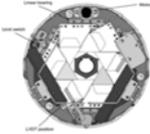


Fig. 3 Our most recent variable aperture design [6]

TABLE I
COMPARISON OF VARIABLE APERTURE DESIGNS

	Ref. [7]	Ref. [8]	Ref. [9]	Ref. [10]	Ref. [11]
Field of application	Solar energy power plants	Energy beam collimators	Radiation control	Photography	Robotic Radio-surgery
Media flow	Solar radiation	Energetic particles	EM radiation	Visible light	X-Rays
Control mechanism	Servo-motor, sliding	Sliding edge contact, gear-driven	Plunger deflection	Step motor, sliding	Drive motor
Aperture structure	Four overlapping blocks	Four blocks sliding edge contact	Flexible members	Two reciprocal sliding blades	Twelve prism-shaped segments
Material	Thick insulating material	Opaque blocks	Stiff steel or spring material	N/A	Thick insulating material
Cross-sectional exposure	Rectangular	Rectangular	Circular, rectangular	V-shape, square-diamond	Rectangular
Schematic of design concept					

In addition to the mechanism, automatic control, and high temperature resistance aspect, the main difference between our aperture and the aperture concepts given in Table 1 is the purpose of use. To check the feasibility of our aperture concept, we have done optical simulations and found out that the non-circular profile created by the aperture allows much less radiation to go into solar reactor as compared to a circular aperture of the same area. This is because the idealized incident radiation has a circular Gaussian distribution. To avoid this problem, we developed a more circular aperture mechanism as shown in Fig. 3 with eight blades and integrated it with a controls system [5]. That concept consisted of rings and pivot pins. The blades were put in between two rings, where the bottom ring held the blade by fixed pins free to rotate. The top ring had radial slots that actuated the pivot pin on each blade allowing it to equally move all blades to form a circular opening that will increase and decrease the diameter upon rotation of the top ring. We performed TracePro simulation and obtained successful results.

III. OPTICAL METHODOLOGY

Optimum aperture diameter is obtained through a compromise between maximum power intercepted at the aperture opening and minimum re-radiation losses incurred [11]. Higher the flux intensity or irradiation, greater is the temperature attained within the reactor body, which creates higher re-radiation losses. This can be better explained in terms of the Stefan-Boltzmann radiation equation:

$$q = \sigma * A * T^4 \quad (1)$$

where q is the radiation loss, σ is the Stefan Boltzmann constant, A is the aperture area, and T is the internal

temperature of the reactor. Considering minimal re-radiation losses, the only two variables in this equation are the aperture area and the internal temperature. To maintain a constant internal temperature, we kept the incoming power constant at 5kW while the aperture diameter is varied from 20 mm to 50 mm and then 50 mm to 80 mm.

Another important concept is the absorption efficiency, $\eta_{absorption}$, which denotes the difference between power intercepted by the aperture and power re-radiated through the aperture in order to maintain a constant internal temperature divided by the total incoming power from the 5kW source.

$$\eta_{absorption} = \frac{\alpha_{eff} P_{aperture} - \epsilon_{eff} \pi^2 \sigma T^4}{P_{in}} \quad (2)$$

where α_{eff} and ϵ_{eff} are the effective absorptance and emittance of the receiver with values of 0.95 each, $P_{aperture}$ is the amount of power intercepted by the aperture, P_{in} is the total power from the source, r is the aperture radius, σ is the Stefan-Boltzmann constant and T is the internal temperature attained within the reactor body.

To emphasize the advantages of variable aperture mechanism, optical simulations were carried out on TracePro, using the Monte-Carlo ray tracing method. The reactor was modeled in SolidWorks and imported into TracePro for optical analysis. A source of 5kW was used as the incoming power and the aperture diameter was varied from 20 mm (small aperture area) to 50 mm (medium aperture area) and finally to 80 mm (large aperture area). The resulting TracePro simulations are displayed in next section with a total of 1 million rays and a ray sorting of 0.01%. In the laboratory, we have an elliptical reflector to concentrate incoming radiation on to a focal point, where the aperture of the reactor is located.

IV. RESULTS AND DISCUSSION

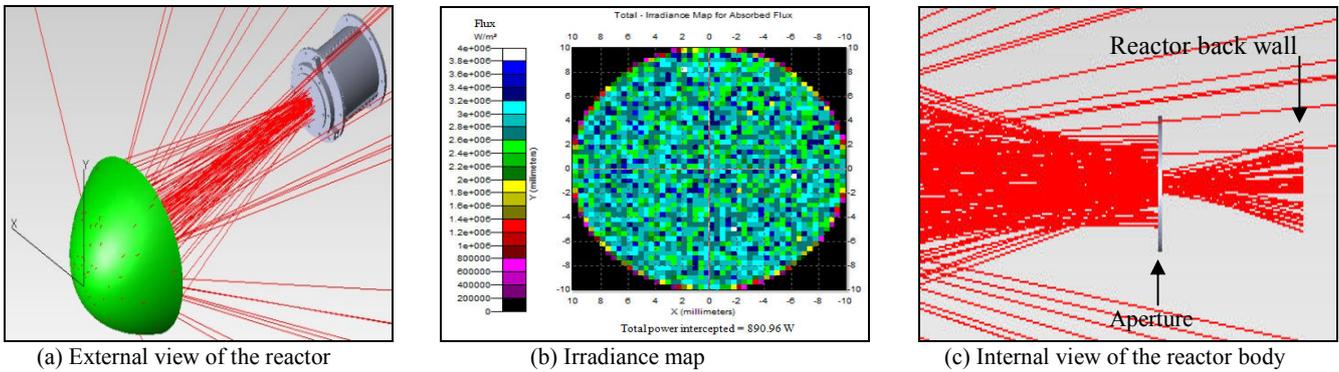


Fig. 4 TracePro simulations for 20mm aperture exposed to 5 kW source

Fig. 4 summarizes the simulation results for aperture diameter of 20 mm at 5 kW incoming solar power. Results show that the total power intercepted at the aperture opening is 890.96 W, which is 17.81% of the incident irradiation. The

low percentage indicates that a lot of incident radiation is reflected back as the aperture opening is fairly small.

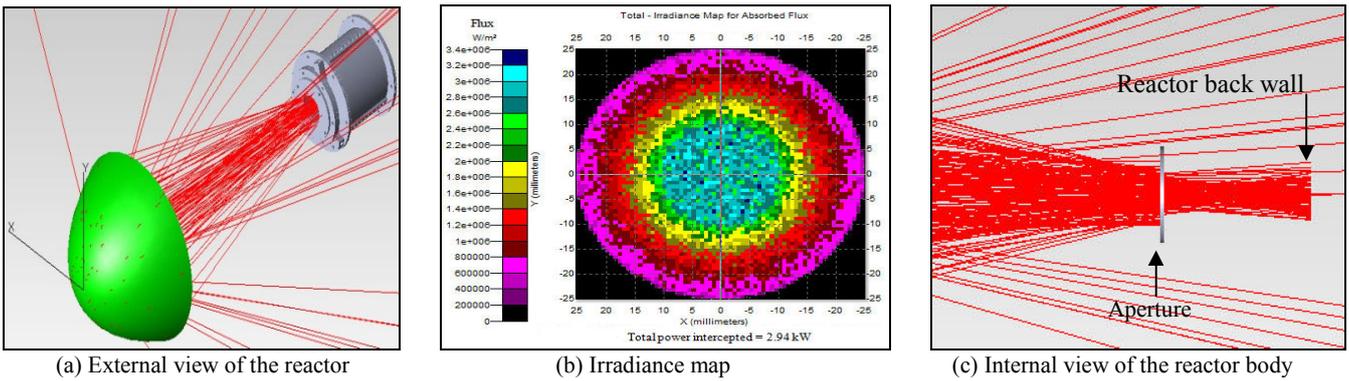


Fig. 5 TracePro simulations for 50mm aperture exposed to 5 kW source

Fig. 5 summarizes the simulation results for aperture diameter of 50 mm at 5 kW incoming solar power. Results show that the total power intercepted at the aperture opening is 2.94 kW, which is 58.8% of the incident irradiation. This

indicates that 50 mm aperture diameter is optimum as there is a good compromise between the power intercepted and the lowered re-radiation losses.

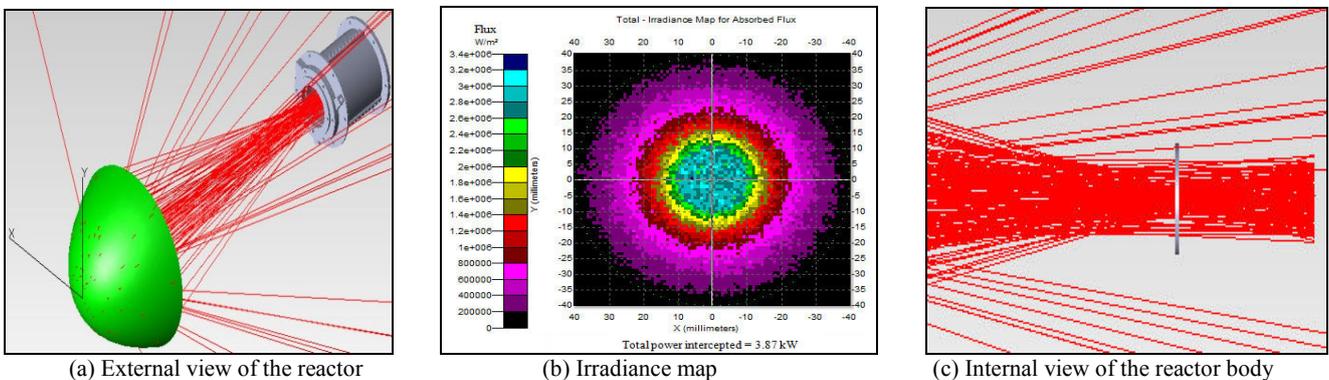


Fig. 6 TracePro simulations for 80mm aperture exposed to 5 kW source

Fig. 6 summarizes the simulation results for aperture diameter of 80 mm at 5 kW incoming solar power. Results show that the total power intercepted at the aperture opening is 3.87 kW, which is 77.4% of the incident irradiation. Although this seems like a much better option, a bigger aperture results in massive re-radiation losses, thereby decreasing the internal temperature of the reactor creating a decrease in energy produced.

From these simulations, it can be inferred that 50 mm is the optimum aperture diameter, as compared to 20 mm and 80 mm. The 50 mm aperture intercepts less power as reduction in aperture area reduces the amount of radiation entering the reactor as well. But from TracePro simulations, we can infer that an optimum area exists where the incoming solar power and the outgoing radiation loss share a good compromise. It can also be inferred that as the area increases, radiation losses dominate thereafter.

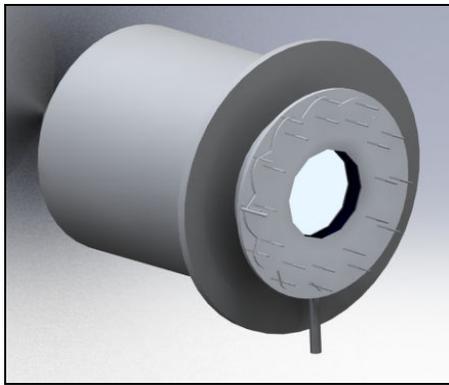


Fig. 7 Aperture opening in a cloudy day – 5 kW

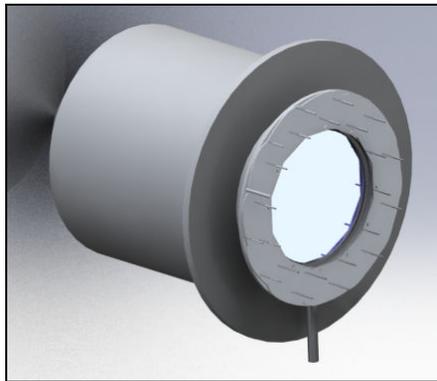


Fig. 8 Aperture opening in a sunny day – 10 kW

Fig. 7 and Fig. 8 illustrates aperture opening in a cloudy day and a sunny day. For a constant internal temperature, when the incoming solar power is low, for example on a cloudy day (5 kW), the aperture reduces in order to reduce the radiation loss. Reducing the area does not drastically decrease the power intercepted. This is because the incoming flux follows a Gaussian distribution with the maximum flux occurring at the center of the aperture area. On sunny days, (10 kW), the reactor aperture opens to increase heat losses so as to maintain a fixed internal temperature.

A low incoming power of 1 kW is not sufficient to maintain an internal reactor temperature of about 1800 K while a very high power of 10 kW causes the internal temperature to rise drastically and results in massive re-radiation losses. Therefore, a balance can be reached by using a radiation source of 5 kW which produces the desired internal temperature and also optimizes the re-radiation losses.

V. CONCLUSION

In this paper, the advantages of variable aperture mechanism over fixed aperture were discussed. Comparisons between present variable aperture designs were made, and an optical analysis for a novel solar reactor aperture concept was presented. The advantages of this new mechanism were validated using optical simulations conducted on TracePro. It was observed that the variable aperture mechanism could possibly minimize the problem of the transient nature of solar insolation. Results obtained from TracePro simulations showed that a constant internal temperature could be maintained by closing the aperture when solar insolation is low, and opening the aperture when insolation is high, in order to minimize re-radiation losses. The peak flux remained unaffected as the incoming flux follows a Gaussian distribution. Finally, a parametric study was presented to identify the optimum aperture diameter. Aperture size between 20 mm to 80 mm diameter was tested and 50 mm was found to be the optimum.

The findings of this study can be summarized as follows:

- With the use of variable aperture concept, semi-constant temperatures inside a solar reactor can be obtained.
- Aperture diameter enlarges when the incoming solar flux is high, and reduces when the flux is low.
- Optimum aperture size is achieved by compromising from the incoming flux and risking re-radiation losses.

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NOMENCLATURE

σ	Stefan-Boltzmann constant
$\eta_{absorption}$	Absorption efficiency
α_{eff}	Effective absorptance of the solar reactor
ϵ_{eff}	Emittance of the solar reactor
$P_{aperture}$	Power intercepted by the aperture
P_{in}	Total power from the source
q	Radiation losses

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