Radiation Intensity Enhancement in a Photoreactor System Coupled to Fresnel Lens

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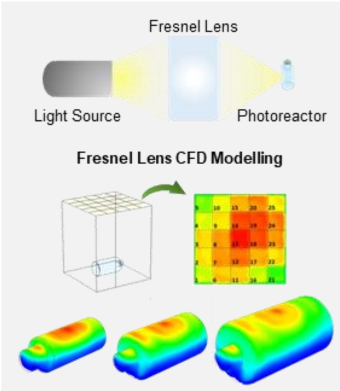

Fresnel lenses are commonly applied to energy systems, in order to promote a better concentration of light into receptors and produce more energy. However, such light concentration capabilities make these types of light concentrators an interesting resource for photoreactors systems, especially those used in water treatment processes, such as water disinfection. This work presents an evaluation of the effects of operating variables in a new photoreactor configuration intended for solar water treatment, through applying CFD modelling and experimental design. Through user-defined routines to reproduce the light path created by the lens, CFD simulations support the data obtained through the 3^k design, and the results herein obtained confirm the high concentration factors provided by Fresnel lenses, presenting new perspectives for the use of different solar concentrators.

Introduction

Among the water treatment technologies, solar-driven processes such as the Solar Water Disinfection (as known as SODIS) have been widely investigated, and the research community has been focused in developing different configurations that intensify the light concentration and also allow a high productivity of safe water [1].

Fresnel lenses usually are associated to energy systems, in which the light concentration provided by the lens is combined with receivers that absorb and transmit the heat, and also in combination with photovoltaic systems, to enhance the amount of electrical energy generated [2]. However, the high concentration capacity of Fresnel Lenses indicates that these solar concentrators may have an interesting application in photoreactor systems for water treatment.

This work therefore aims to shed light on the potential application of this technology in batch reactors (water bottles), assessing the effects of various configurations on the incident radiation inside the reactors by developing computational fluid dynamics routines and experiments.

Material and Methods

Computational Fluid Dynamics (CFD)

The 3D domain was modelled by considering the point Fresnel lens as a wall emitting UVA radiation, and to model the light concentration a user-defined function (UDF) was developed based in the work of Kaddoura and Zeaiter [3], by implementing a 3D approach. As indicated in the Graphical Abstract, the wall corresponding to the Fresnel lens was subdivided in 25 subregions, and in each of them the experimentally measured radiation value was attributed, since the radiant flux provided by the lamp is not homogeneous over the lens surface. The Discrete Ordinate Method (DOM) was employed for the numerical resolution of the Radiation Transfer Equation (RTE) in *Ansys® Fluent* v.14.5 [4], and the angular discretization of 15x15 ($N_\vartheta x N_\Phi$) was the best trade-off found for the model. The domain was subdivided into hexahedral (reactor volume) and tetrahedral elements, with minimum element sizes of 1.27 mm and 3.65 mm, respectively for reactor and domain volume, determined as small enough to provide grid independent results.

Lamp Experiments

Both the CFD model and the experimental rig employs a 131x131 mm point Fresnel lens, with a collection area of 17,161 mm^2 and a focal point at 135 mm. The photoreactors evaluated in the study were glass vials of 15 mL, 39 mL, and 62 mL, in order to assess the effect of the volume in the average radiation intensity within the reactor. Three different distances between the photoreactor and the lens were employed: 30 mm, 82.5 mm, and 135 mm (focal point). Therefore, a 3^k factorial design was performed to verify the effects of the abovementioned variables in the incident radiation within the reactor. The light source consisted in a 1000 W halogen lamp coupled to a parabolic aluminized reflector. Actinometry experiments with potassium ferrioxalate were performed with the vials at maximum exposure times of 200 seconds to avoid heating the solution beyond the actinometer's validity range [5].

Results and Discussion

Table 1 shows the incident radiation values obtained from the 3^k factorial design and the concentration factor (FC) provided by the lens. The concentration factor consists in the ratio between the radiation measured in the reactor and the radiation incident on

the lens surface. In the design performed, values up to 12.20 for the FC were found, confirming the high concentration capability of point Fresnel lenses.
Such high value was observed for the combination of the smallest reactor volume (V_R) with the highest distance from the lens (D_L), the later corresponding to the focal distance. Naturally, when observing a light profile provided by a Fresnel lens, the highest radiation values can be visualized in the focal point.

Table 1. Radiation Intensity (I) results for reactor volume (V_R) and lens distance (D_L) in the 3^k factorial design.

#	V_R (mL)	D_L (mm)	I (W/m²)	FC (-)
1	15.0	30.0	19.26	1.92
2	15.0	82.5	77.90	7.80
3	15.0	135.0	122.06	12.20
4	39.0	30.0	14.41	1.44
5	39.0	82.5	63.84	6.40
6	39.0	135.0	85.80	8.60
7	62.0	30.0	19.94	2.00
8	62.0	82.5	50.00	5.00
9	62.0	135.0	66.67	6.66

This behavior can be observed in the response surface plot presented in Figure 1. The equation obtained shows a parabolic effect for the DL variable, indicating the existence of a maximum value for this variable, which is located at the focal point, thus reproducing the concentration effect observed in Fresnel lenses, in which after the focal point the light rays begin to diverge.
As the volume increases, the radiation within the vial tends to decrease substantially, as can be seen in runs 3, 6, and 9 of the factorial design, and in Figure 2, which shows the contours of radiation intensity for the corresponding CFD simulations performed. At smaller D_L values, the vial is with the cone reach of the light path promoted by the lens, leading to a better light distribution inside the reactor, but with smaller radiation intensities.

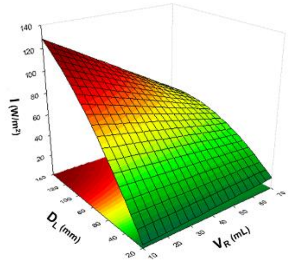

Figure 1. Response surface plot showing the effect of operating variables on Radiation Intensity within the.

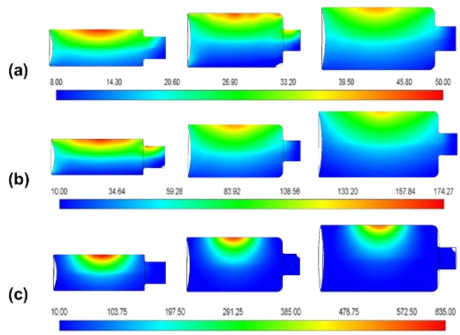

Figure 2. Radiation Intensity (W/m²) contours for runs: a)1, 4, 7; b)2, 5, 8; c) 3, 6, 9.

Another aspect visualized from the CFD plots it that although the axial center of the vials was positioned at the focal point of the lens, for runs 3, 6, and 9, the highest radiation values come out near the walls of the vials, and as the light path moves away from the wall it loses intensity, thus generating a high radiation spot that contributes to increasing the average value inside the reactor. Despite this uneven light distribution, the possibility of positioning the reactor at the focal point of the lens, increasing the average radiation intensity, can be an advantage of this concentrator type over other concentrators like compound parabolic collectors (CPCs). The magnitude of the radiation gradient inside the reactor can be minimized by working with smaller reactor volumes, however, for the purposes of treated water productivity, recirculation systems may become necessary.

Conclusions

The high concentration power promoted by Fresnel lenses has great potential for application in systems with photoreactors for solar treatment. The results presented in this work demonstrate that although some effects related to the use of these lenses are naturally predicted, such as the focal length, the reactor volume plays an important role in maintaining homogeneous radiation levels inside the reactor. The operation of smaller volumes at the focus of the lens leads to maximum values of radiation intensity within the reactor, and recirculation systems can be an alternative to increase the productivity of treated water in such configurations.

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