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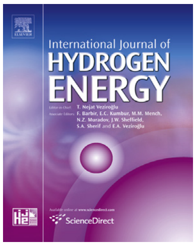

Solar concentrator with uniform irradiance for particulate photocatalytic hydrogen production system

Yan Yang, Qingyu Wei, Junyi Hou, Huan Liu, Liang Zhao*

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, China

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ABSTRACT

The solar concentrator is an essential part of the particulate photocatalytic hydrogen production system (PPHS). In this study, a mathematical model was developed and applied to avoid non-uniform concentration of solar intensity on the receiving surface of a compound parabolic concentrator (CPC). The reflector profile curve was calculated via a first-order differential equation. The geometric concentration ratio and bottom interval parameters were changed to optimize the surface uniform concentrator (SUC). The overall performance of the concentrator was then assessed based on the optical efficiency and uniformity on the receiver in ray tracing software. A prototype of a SUC was manufactured to validate the calculation results. It is found that the conversion efficiency of solar energy to hydrogen with the SUC was 8.57% higher than that of the CPC.

Introduction

The search for innovative, sustainable energy is undoubtedly one of the most important – and urgent – endeavors faced by the scientific community today. The fuels used to power anthropogenic activities move through three stages: from solid, to liquid, to gas; to be precise, from carbon to hydrogen. Pure hydrogen is considered an indispensible energy carrier due to its high energy density, "clean" properties, and convenience of storage and transport [1]. Combining the advantages of solar energy and hydrogen represents one of the most effective approaches to clean and renewable energy. Photocatalytic hydrogen production from water using solar energy is a relatively common technique for doing so. Photoelectron chemical decomposition of water for hydrogen production was first discovered by Fujishima and Honda [2], and the concept and methodology have since been extended to modern particulate systems for heterogeneous photocatalysis [3].

There are two key functions which apply to photocatalytic hydrogen production technology: One is the use of a well-designed photocatalyst, and the other is the full and efficient use of solar energy. In recent years, researchers have focused on the activity and stability of photocatalysts by improving the preparation process and modification methodology. Extensive research has been conducted on surface sensitization, energy band modulation, noble metal deposition, and semiconductor coupling for these purposes [4–7]. As far as the use of solar energy, to increase the solar intensity on the receiving tube the solar concentrator is also an integral part of

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* *Corresponding author.*
E-mail address: lzhao@mail.xjtu.edu.cn (L. Zhao).

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the system. At present, there are four types of solar concentrators used most frequently: the tower, parabolic dish, parabolic trough and compound parabolic concentrator (CPC). The first two concentrators are mainly used for solar energy utilization at high temperatures. Nevertheless, the condition of photocatalytic reaction system for hydrogen production requires low temperature and ordinary pressure conditions. However, the latter two solar concentrators are mainly used for photothermal conversion and the photocatalytic detoxification or degradation.

Bakos designed a representative line-focused parabolic-trough solar-collector for the solar steam-generation [8]. The performance of a parabolic trough photovoltaic/thermal collector was analyzed by Coventry [9]. The solar energy flux distribution on the receiving tube of a parabolic solar collector was simulated by Cheng via Monte Carlo Ray-Trace Method [10]. The first European industrial-scale solar detoxification system of hazardous and non-biodegradable water contaminants was created by Blanco based on CPC [11]. Malato later discussed the technical feasibility and performance of photocatalytic degradation of water-soluble pesticides using CPC [12]. The absorption of solar radiation in the reactors was analyzed by Colina-Marquez based on CPC [13]. Researchers in Spain and Jordan have established solar disinfection reactors together with CPC [14,15]. A photocatalytic hydrogen production solar reactor based CPC had been designed by Jing for the first time [16].

The research on the catalyst-liquid particulate flow in the photocatalytic reactor for hydrogen production has been carried out by Hu [17] and Jing [18]. The state of catalyst-liquid will be achieved in a fully developed flow due to the effects of turbulence force. It is commonly accepted that the trough and CPC are line focus collectors, the irradiation is extreme non-uniform distributed on the surface of receiving tube. Nevertheless, this phenomenon is not fit for the photocatalytic reaction according to the first law of photochemistry [19]. Moreover, photocatalyst photocorrosion, which is accelerated under elevated local temperature, critically affects steady operation during the reaction process, especially for metal sulfide photocatalysts [20,21]. Most uniform concentrators in use in existing solar power systems are flat-plate receivers, especially for photovoltaic cells. Akbarzadeh and Wadowski, for example, designed a uniform concentrator suitable for the flat receiver [22]. There has been relatively little research to date on uniform sunlight illumination on the surface of the receiving tube, i.e., innovative concentrator design. Rabady recently did propose a solution to this problem, but achieved uniform sunlight concentration on only 64% of the surface area [23].

In this study, we attempted to solve the uniform concentration problem for the whole surface area of the receiving tube. In order to simultaneously ensure the optical efficiency of the concentrator and realize a uniform radiation distribution on the receiving tube, a design method of concentrator was proposed. A mathematical model of the reflector profile was established according to reflection and energy conservation laws. The surface uniform solar concentrator (SUC) was optimized by investigating geometric concentration ratio and bottom interval parameters. The overall performance of the concentrator was then assessed based on the optical efficiency and uniformity on the receiver in ray tracing software. For comparison, a particulate photocatalytic hydrogen production system (PPHS) based on the SUC and the CPC was established. Then, using $Cd_xZn_{1-x}S$ as a model photocatalyst, the performance of hydrogen production was discussed.

Mathematical model

The cross-section geometry of a typical reflector is shown in Fig. 1. The center of the receiving tube is the origin of the Cartesian coordinate system; the reflector profile is composed of curves *AB* and *CD* and straight line *BC*. *AB* and *CD* are symmetrical with respect to the *y* axis, and *BC* is parallel to the *x* axis.

The optical performance of the SUC was evaluated by ray tracing technology. During ray tracing analysis, each incident ray was assumed to be parallel to the others and to carry the same energy. The radius of the receiving tube and the geometric concentration ratio are expressed as *b* and *CR* respectively, so the coordinates of points *B* and *A* are represented as $(b,\ c_1)$ and $(CR \cdot \pi b,\ c_2)$, respectively, as shown in Fig. 2. Assuming that one of the incident rays intersects the profile at point $M\ (x, y)$ and the reflected ray intersects the receiving tube at point $N\ (x_b, y_b)$, the central angle of corresponding arc *PN* is θ_N.

The vector form of the law of reflection for the purposes of ray tracing can be expressed as follows:

$$\left[2-2\left(\overline{O}\bullet\overline{I}\right)\right]^{1/2}\bullet\overline{N}=\overline{O}-\overline{I}, \tag{1}$$

where *I* is the unit vector of incident light, *O* is the unit vector of reflected light, and *N* is the normal unit vector of the reflector curve. The three vectors shown in Fig. 2 correspond to the following equations:

$$\overline{I}=(0,-1), \tag{2}$$

$$\overline{O}=\frac{1}{\sqrt{(x_b-x)^2+(y_b-y)^2}}(x_b-x, y_b-y), \tag{3}$$

$$\overline{N}=\frac{1}{\sqrt{dx^2+dy^2}}(-dy, dx). \tag{4}$$

Substituting Eqs. (2)–(4) into Eq. (1) yields the following:

$$\frac{dy}{dx}=f(x,y)=\frac{x-x_b}{y_b-y+\sqrt{(x_b-x)^2+(y_b-y)^2}}. \tag{5}$$

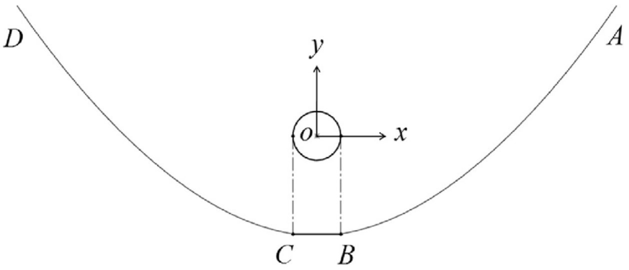

Fig. 1 – Geometrical configuration of the reflector profile.

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