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Wirelessly powered ultraviolet light emitting diodes for photocatalytic oxidation

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ABSTRACT

A method is presented to distribute small scale light sources in a photocatalytic slurry reactor. The goal of distributing the light sources is to increase photon transfer efficiency, and thereby increasing the reaction rate, compared to using one single light source. The light sources used in this study were ultraviolet light emitting diodes with a wavelength of 375 nm. An up-flow of air into the photocatalytic reactor distributes the UV-LEDs throughout the reactor, mixes the reaction solution and saturates the solution with molecular oxygen. To make distribution of the UV-LEDs possible, the UV-LEDs were powered wirelessly by resonant inductive coupling. This article shows that UV-LEDs distributed throughout the reactor show a 30% higher removal rate of methylene blue compared to the UV-LEDs concentrated on one plane in the reactor. The removal rate increased linearly with increasing numbers of UV-LEDs. The size of the UV-LEDs determined that up to 32 UV-LEDs could be wirelessly powered in a reactor volume of 500 ml. To increase the reactivity, a higher amount of UV-LEDs per reaction liquid volume and higher radiant power of the UV-LED can be used, bringing use of photocatalytic reactors closer to industrial applications.

1. Introduction

Reuse and safe disposal of treated wastewater is an important topic in a world of growing pressure on water resources [1]. Macropollutants, but also micropollutants, pathogenic bacteria and viruses have to be removed for safe reuse or disposal of wastewater [2]. Macropollutants are removed by conventional aerobic or anaerobic treatment but micropollutants, pathogenic bacteria and viruses need an additional treatment process [1]. A suitable processes are advanced oxidation processes (AOPs) for the removal of micropollutants, pathogenic bacteria and viruses. A promising AOP is heterogeneous photocatalysis.

Heterogeneous photocatalytic oxidation is a promising technology for advanced water treatment. Many studies have shown that photocatalytic oxidation can be used to oxidize, reduce or to transform a range of organic pollutants [3,4], inorganic pollutants [5], pathogenic microorganisms and viruses [6]. Photocatalysis can be considered a sustainable treatment process as it uses a reusable solid state photocatalyst, produces no waste and uses photons as energy source. Photocatalysts are solid state semiconductors, e.g. titanium dioxide (TiO_2), or zinc oxide (ZnO). The electrons in the valance band of a photocatalyst can be excited to the conduction band by a photon with an adequate energy level (>3.2 eV for TiO_2), leaving an electron–hole pair. The electron–hole pair can act as a site for active oxidation and reduction of compounds or the electron–hole pair can react with water to produce hydroxyl radicals and other species that oxidize or transform dissolved compounds.

Much work on heterogeneous photocatalytic oxidation is done in the laboratory, but industrial implementation is still limited and on small scale [7]. The main issues preventing industrial application of heterogeneous photocatalytic oxidation are the development of photocatalytic reactors with good mass transfer, photon transfer and the ability for up-scaling [8–10]. Many different types of photocatalytic reactors were developed but the reactors demonstrate either good mass transfer or good photon transfer but not often both [9,10]. Research to achieve higher mass transfer has resulted in significant advances with spinning disk reactors [11], monolith reactors [12] and micro-reactors [13,14].

Research to increase photon transfer is an important topic in photocatalytic oxidation. Photon transfer is the ability of a photocatalytic reactor to illuminate the surface of a photocatalyst. A photocatalytic reactor that illuminates a high surface area per reaction liquid volume with a homogeneous

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distribution of the light has good photon transfer. Ray and Beenackers [15] introduced a parameter (κ) to indicate the amount of illuminated surface per unit of reaction liquid volume inside the reactor ($m^2_{ill}/m^3_{reactor}$). Many different types of reactors have been proposed to increase the illuminated surface area per reaction liquid volume, e.g. slurry reactors (2631–170,000 m^2/m^3), annular reactors (27–2700 m^2/m^3), optical fiber reactors (46–2000 m^2/m^3), monolith reactors (900–1300 m^2/m^3), spinning disk reactors (50–66,000 m^2/m^3) and microreactors (7300–250,000 m^2/m^3) [8]. There is a huge difference between the reported values of κ depending on the reactor type but also on the way the illuminated surface per volume is calculated. The value of κ can differ a lot by underestimating or neglecting the non-illuminated surface in the reactor. Van Gerven et al. [8] suggests a different parameter to compare photocatalytic reactors, illumination efficiency, η_{ill}, including the illuminated surface per volume (κ, m^{-1}), the average incident radiant power and the incident uniformity.

$$\eta_{ill} = \kappa \frac{P_{cat}}{P_{lamp}} \frac{A_{minE}}{A_{cat}} \quad (1)$$

With P_{cat} the power received at the catalyst surface, P_{lamp}, the power the lamp radiates, A_{minE}, the surface area receiving the minimal amount of energy and A_{cat}, the total amount of surface area.

In a slurry-type photocatalytic reactor the photocatalyst is suspended as a fine powder in the reaction liquid. The suspended fine powder gives a high surface area resulting in good mass transfer from the bulk of the liquid to the surface of the photocatalyst particle. The photon transfer, however, is poor due to the strong absorption and scattering of light by the suspension. The light penetration is very shallow and results in a small amount of illuminated photocatalyst particles by a single lamp. We attempt to increase the photon transfer by using a multitude of small-scale light sources of micro-scale as suggested previously by Van Gerven et al. [8]. The small-scale light sources are distributed homogeneously in the suspension resulting in a high illuminated surface area.

Ultraviolet light emitting diodes (UV-LEDs) are used as small-scale light sources and have been investigated as light sources for photocatalytic oxidation in recent studies [16]. The most recent generation of UV-LEDs emit light with wavelength of 375 nm, have similar energetic efficiencies and similar lifetime as low pressure mercury discharge lamps and black light lamps. The UV-LEDs are expected still to be further developed while low pressure mercury lamps regarded as fully optimized. Advantages of UV-LEDs over low pressure mercury lamps are compact size, robustness against mechanical shocks and availability of in different emitted wavelengths [17]. Simply replacing the low pressure mercury lamps by UV-LEDs and not changing the reactor design does not solve the fundamental problems of photocatalytic reactors. Because of the small size of the UV-LEDs the possibilities to design photocatalytic reactors enable otherwise impossible designs compared to conventional UV lamps.

This research focuses on developing a novel photocatalytic slurry-type reactor where a high number of UV-LEDs are distributed throughout a reactor volume. The wireless UV-LEDs are powered by resonant inductive coupling (RIC) with a small receiving inductor connected to the UV-LED (receiving circuit) which is inductively coupled to a transmitting inductor, placed around the reactor. A well-known application of RIC is charging of electrical toothbrushes [18], but RIC is thought to be advantageous for many other applications, e.g., biomedical equipment [19], mechatronic systems [20], household electronics, charging batteries of portable devices [21], charging batteries of electrical powered automobiles and busses [22], and sensors.

One advantage of powering UV-LEDs with RIC is that the UV-LEDs, without any physical connections, will have freedom of movement. In previous studies we showed that a multitude of small receiving inductors submerged in water can be powered with one larger inductor with an energy transfer efficiency of >75% [23]. The conductivity and permittivity of water does not show a negative impact on the energy transfer efficiency [24].

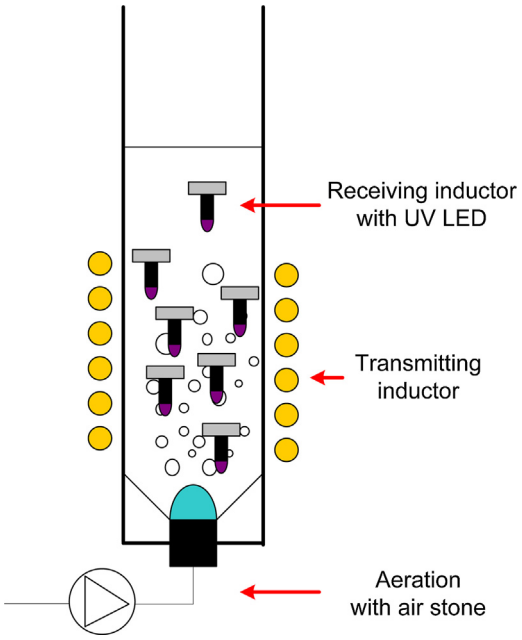

Fig. 1. Schematic drawing of the photocatalytic reactor with aeration, transmitting inductor and the receiving inductor with UV-LED.

In this article the characteristics of the novel photocatalytic slurry type reactor were studies. We investigated: (i) the influence of distributing the UV-LEDs in the reactor compared to concentrating the UV-LEDs on one plane in the reactor, (ii) the influence of aerating on the reaction rate, (iii) the influence of the number of UV-LEDs on reaction rate, on κ and η_{ill}, and (iv) the influence of the number of UV-LEDs on the energy efficiency.

2. Materials and methods

2.1. Inductive powering UV-LEDs

In a previous article, we discussed theoretical calculations supported with experimental results on how to optimize the energy transfer efficiency for linear resistive loads [23]. The resistance of the load is not defined in case of nonlinear electronic components like LEDs. The equivalent load resistance of the LED can be calculated from the measured energy transfer efficiency.

2.2. Photocatalytic reactor

The photocatalytic reactor was a PVC tube with a diameter of 0.075 m and height of 0.2 m. The transmitting inductor was wound around the outside of the tube as a solenoid as can be seen in Fig. 1. At the bottom of the reactor air was supplied through an air stone. All photocatalytic activity experiments were done with a solution of 500 ml in batch mode.

2.3. Resonant inductive powering

The operating frequency of the AC applied to the transmitting inductor was 45 kHz. The AC source was a TG2000 Function Generator from AIM & Thurlby Thandar Instruments, which signal was amplified by a type AB amplifier from Thell, type Accusound 101. The AC source was connected to a three loops inductor which was