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SCIENCE DIRECT
Applied Catalysis B: Environmental 65 (2006) 57–65
APPLIED CATALYSIS B: ENVIRONMENTAL
www.elsevier.com/locate/apcatb

Enhanced photocatalytic disinfection of indoor air

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Received 18 May 2005; received in revised form 19 September 2005; accepted 24 October 2005
Available online 15 December 2005

Abstract

A silver ion doped TiO_2 based photocatalyst, with improved destruction of airborne microbes, has been developed. The performance of the silver ion doped photocatalyst is demonstrated using a catalyst coated filter in a recirculating air experimental facility. *Bacillus cereus*, *Staphylococcus aureus*, *Escherichia coli*, *Aspergillus niger*, and MS2 Bacteriophage have been used as indexes to demonstrate the high disinfection efficiency of the enhanced photocatalysis process. The microbial destruction performance of the enhanced photocatalyst is found to be an order of magnitude higher than that of a conventional TiO_2 photocatalyst. The process of enhanced photocatalysis can thus be used effectively against high concentrations of airborne microorganisms, making it an attractive option as a defense against bio-terrorism.

Keywords: Photocatalysis; Disinfection; Indoor air; Airborne microorganisms; Silver ions

1. Introduction

Air Filtration and Purification World Markets predicted that the world market for air filters would rise to US $5 billion in 2005. This rise can be attributed to the security efforts to counter chemical and biological terrorism, as well as the increased awareness of the people towards environment and environmental pollution. In 2000, a document published by the World Health Organization (WHO) stressed that it is our human right to breathe healthy indoor air [1]. It further emphasizes that ensuring acceptable indoor air quality is the responsibility of all concerned. A study done by the US Environmental Protection Agency (EPA) in 1987 concluded that indoor air pollution poses a greater risk than outdoor air pollution [2]. This indoor air pollution is estimated to be the cause of several health related issues and reduced work productivity among people.

Allergies and diseases such as asthma and sick building syndrome (SBS) have increased considerably over the last few decades. A recently concluded European survey of around 140,000 individuals in 22 countries shows that this increase is dependent on the environment and the lifestyle of the individuals. Because most of the Americans spend a substantial amount of time indoors, indoor air contamination poses a serious threat to them. Microbial agents in indoor air are considered a serious health hazard and therefore microbial contamination of indoor air has been the major topic of attention in recent times [3]. One of the biggest disease outbreaks due to microbial contamination of indoor air was the Legionnaires' disease outbreak in Philadelphia in 1976 [4]. Also, the recent bio-terrorism threat due to anthrax has fueled huge interest in new technologies for indoor air disinfection.

Advanced oxidation technologies, in particular the photocatalytic technology offers several environmental and practical advantages over conventional biological or physical disinfection processes. The huge interest generated by photocatalysis has motivated several researchers to look into the basic mode of action of TiO_2. TiO_2 is a semiconductor with a band gap close to 3.2 eV. UV light with wavelengths shorter than ~380 nm photoactivates TiO_2 by providing the band gap energy needed by an electron to jump from the valence band to the conduction band. This implies that when photons of UV light are absorbed on TiO_2, they generate excited pairs of electrons and holes. The photogenerated holes react with the water to produce hydroxyl radicals ($^{\bullet}OH$), while the photogenerated electrons react with molecular oxygen to give superoxide radical anions ($^{\bullet}O_2^-$). These radicals so produced are highly reactive and they work together to completely oxidize the organic species. The attack by the $^{\bullet}OH$ radical, in the presence of oxygen, thus initiates a

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doi:10.1016/j.apcatb.2005.10.025

Nomenclature

cfu	colony forming units
CC_i	averaged initial colony count
CC_t	averaged colony count after a specific time interval '*t*'
eV	electron volt
EPA	Environmental Protection Agency
EHS	Environmental Health and Safety
$^{\bullet}OH$	hydroxyl radical
$^{\bullet}O_2^{-}$	superoxide radical
t	time of exposure
TSA	Trypticase Soy agar
TSB	Trypticase Soy broth
UV	ultraviolet radiation

complex cascade of oxidative reactions. The mechanism of the photocatalytic process has been extensively studied in the literature and several complex reaction pathways have been reported [5–8]. Although the exact mechanism of the process and the reaction pathways are still not clear, the practical applications that these processes offer have fueled enormous commercial interest. Recent review articles provide a comprehensive coverage of the application of TiO_2 photocatalysis to disinfection [9–12].

The pioneering work in the field of photocatalytic disinfection of indoor air was done by Goswami et al. when they developed a technology to completely destroy biological contaminants in indoor air. A recirculating duct facility was used, wherein the bacteria (*Serratia marcescens*) was shown to be completely destroyed [13,14]. Subsequent research conducted by Goswami et al., with improved reactor designs, demonstrated 100% destruction of *Serratia marcescens* bacteria in a much reduced time [15]. Their group even reported inactivation of dust mite antigens by photocatalytic oxidation. *Der p II* was selected and its fast destruction demonstrated the ability of the photocatalytic technology to control allergies and diseases in the population [16].

The photomineralization of bacteria on a photocatalytic surface in air was first shown by Jacoby et al. They studied photooxidation of *Escherichia coli* and found 54% mineralization in 75 h by measuring the carbon dioxide released [17]. Also in their most recent studies, Wolfrum et al. demonstrated complete mineralization of *E. coli*, *Micrococcus luteus*, *Bacillus cereus* (bacterial cells and spores), and *Aspergillus niger* spores by photocatalytic oxidation. They based their results on kinetic data and carbon mass balance [18].

In 1999, Masaki and coworkers reported destruction of bacteria and foul odor in air using stainless steel plates coated with thin films of TiO_2 [19]. Photocatalytic disinfection in gas phase was further illustrated by Lopez and Jacoby in 2002. They showed destruction of *E. coli* in a contaminated air stream as it was passed though a self-cleaning metal microfibrous mesh filter coated with TiO_2 [20]. Greist et al. demonstrated the capability of photocatalytic oxidation to destroy *B. anthracis* (Anthrax) through the successful destruction of *B. subtilis* spores [21]. Following the recent attack of SARS virus, Howells studied a system, based on photocatalytic disinfection, to control the spread of infectious microorganisms such as SARS virus on flights [22]. Most recently, Lin and Li investigated the disinfection effectiveness of commercial titanium dioxide coated filters for airborne microbes. They studied the destruction of nebulized *E. coli* (gram negative bacteria), *B. subtilis* (bacterial spores), *Candida famata* (yeast), and *Penicillium cetrinum* (fungal spores) in a laboratory setup and concluded that the process was effective against airborne microorganisms [23].

The intent of this study was to enhance the overall rate of destruction of the photocatalytic process, and to make it commercially more attractive as a defense against bio-terrorism in indoor air environments. An efficient way to improve the kinetics of photocatalysis is the addition of transition metals to TiO_2 [6]. Introduction of metal ions in the lattice of TiO_2 has shown significant enhancement in the photcatalytic activity of TiO_2 for the degradation of various organics. Iron(III) doped TiO_2 [24,25], platinized TiO_2 [26,27], lanthanide metal ion doped TiO_2 [28], chromium doped, manganese doped and cobalt doped TiO_2 [29], and silver doped TiO_2 [30–32] have all been successfully demonstrated as photocatalysts leading to an increased rate of destruction of organics.

Although there is extensive literature on the use of silver ion doped TiO_2 for photocatalytic degradation of organics, its application for photocatalytic disinfection in gas phase has not been studied much. It is widely recognized that Ag^+ ions possess anti-microbial properties and the work done by Sokmen et al. demonstrated the enhancement in inactivation of *E. coli* in liquid phase using $Ag–TiO_2$/UV system [33].

The main aim of this study is to demonstrate the effectiveness of silver ion doped TiO_2 photocatalyst for fast inactivation of a wide range of airborne microorganisms in a recirculating air experimental facility with the enhanced photocatalyst, and compare it with the performanace of conventional Degussa P25 TiO_2 photocatalyst. The Ag^+ ions from the dopant act as an electron trap in the photocatalysis process. This reduces the recombination between electrons and holes, and thus results in an increased availability of holes. The synergistic effect of the doped Ag^+ ions, and highly oxidizing radicals generated by TiO_2 photocatalysis process, may lead to a highly enhanced rate of microbial destruction.

2. Materials and methods

2.1. Experimental facility

The recirculating experimental setup designed for this study is illustrated in Fig. 1. The apparatus consists of a recirculating duct, a reactor section and a blower with a belt driven motor to circulate air through the duct facility. The upper portion of the recirculating duct is rectangular in cross section while the lower duct portion is circular. The whole duct is designed to ensure uniform air flow through the duct with minimum separation, which would otherwise lead to dead spaces in the duct where