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Comparative study of performance efficiency for three kinds of photoreactors*

Wang Yi-zhong, Fu Yuan, Tang Hong-xiao

State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

Abstract—This paper generalized the structure characteristics of three different configuration photoreactors: annular-type irradiated by lamp, solar shallow-pond and solar flat-plate and compared their performance efficiency at the same reaction condition level which was determined by the first order rate constant in photocatalytic decolorization of methyl orange in TiO_2 suspension. It was demonstrated that solar could be considered as an alternative light source in photoreactors not only for low running and construction cost but also for their successful performance. The evidence has proved the feasibility of solar photocatalytic oxidation as an additional or alternative advantage stage of wastewater treatment process.

Keywords: photoreactor; photocatalytic oxidation; wastewater treatment.

1 Introduction

Since 1976 Carey reported his successful result about PCBs compounds to be photocatalytic dechlorinated photocatalytic oxidation of organic compounds by semiconductor oxides such as TiO_2 has been attracted attention for treating contaminated water. A wide range of organic compounds can be mineralized to carbon dioxide or transformed to less toxic compounds (Blake, 1994; 1995; Legrini, 1993; Venkatardi, 1993). The possibility of photocatalytic detoxification as an alternative method for clean-up polluted water has been proved (Hoffmann, 1995). Lately, considerable attention has been focused on the utilization of combining heterogeneous catalysis with solar technologies (Assmann, 1994; Fell, 1994; Hecht, 1990; Schiele-Trauth, 1994) as well as the design and performance of various photoreactors (Wyness, 1994). Electrically powered UV light had been used mainly in developed countries because of its advantages such as controllable, comparable and stability. However, it is likely to be limited for industrial application because of its high treatment cost. In contrast, there has been great interest in developing solar photocatalytic oxidation facilities for industrial wastewater treatment. The UV component <380 nm of the solar spectrum (contain 3.47% in total) can drive photocatalytic oxidation reaction of organic compounds on the TiO_2 surface. Since water vapor does not absorb UV radiation solar photoreactor perform well under both sunny and cloudy atmospheric conditions.

The objective of this investigation is to compare the performance efficiency and operation condition for different photoreactors in order to put forward design recommendation for industrial application. Three photoreactors designed with different configurations using powered UV lamp and solar energy was investigated respectively.

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2 Apparatus and reagents

Methyl orange having azo and quinonoid structures, which is main structure of most dye compounds, was chosen as test compound. The performance efficiency was tested by comparing the first-order rate constant in photocatalytic decolorization of methyl orange in an aqueous solution with initial concentration 20 mg/L. The catalyst used in all test is TiO_2 reagent powder (made in Beijing Chemical Industry Company; predominate anatase). The incident UV radiation both of mercury lamp and of solar outdoors was measured with a UV irradiance meter (model UV-A made in Beijing Normal University) with wavelength range: 320—400 nm and recorded with a recorder. Outdoors tests were done around noon time so that the UV insolation did not vary significantly over the duration of a test. In order to compare the operation condition each test a time-average UV insolation was calculated. The colour removal of methyl orange solution was measured by a colorimeter (Cole Parmer) after separating the solution and catalyst with centrifuge and 0.45 μm filter.

3 Characteristics of three photoreactor

3.1 The cylindrical annular-type photoreactor irradiated by powered UV lamp

The photoreactor showed as Fig.1 was made of Pyrex glass. A middle pressure mercury lamp 500 W or 300 W (made in China) was inserted in the midst chamber. The outside is reaction container with about 600 ml volume. Cooling thimble was between the lamp and reaction vessel to keep the temperature of reaction solution unchanged by running tap water pass through. Available spectrum of light source can be controlled in visible light 330—450 nm or in UV and visible 200—450 nm by change glass and quartz cooling thimble. Air was bubbled into the solution at 240 ml/min flow rate to provide with the soluble oxygen and to improve the heterogeneous mixing. TiO_2 powder (1 g/L) were suspended in solution by a magnetic stirrer. Fig.2 shows the effect of different power of light source on the decolorization reaction rate of solution. It is found that the ratio of incident UV intensity for 500W to 300W lamp is 1.8, but the ratio of both reaction rate constants under both incident UV light K_{500} to K_{300} is 2.4. It means that the rate of photocatalytic reaction is proportional to the power of light source and it will be more economical efficient using bigger power of UV lamp. Fig.3 shows the comparison data of both reactions using glass and quartz cooler with 500W lamp at the same condition as above. The ratio of both UV intensity through glass and quartz cooler is 1.9 and the ratio of both rate constants using different cooler is 4.3. It indicates that as the material of photoreactor quartz is more advantage than Pyrex glass.

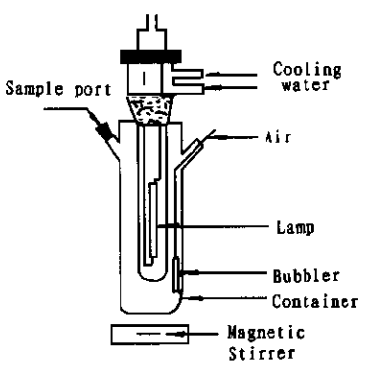

Fig.1 Diagram of cylindrical annular type photoreactor

3.2 Solar shallow pond photoreactor

The solar photocatalytic experimental facility consists of different glass container open to atmosphere with different aperture to volume ratio. Here the aperture refers to the surface area of the liquid/air interface. Catalyst was mixed with reaction solution by magnetic stirrer. Tests were

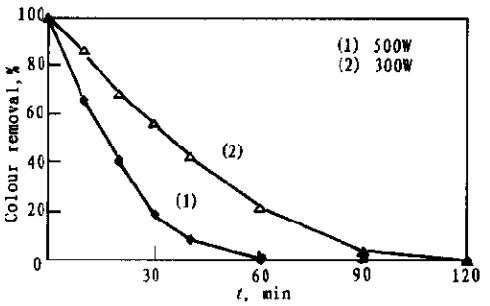

Fig.2 Effect of light power on colour removal

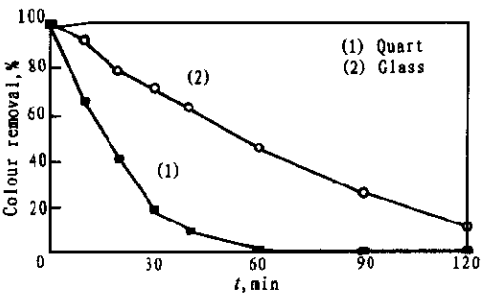

Fig.3 Effect of different cooler on colour removal

carried out in autumn 1996 in Beijing. It was found that the reaction rate constant increases with increasing the aperture to volume ratio as shown in Fig.4. When operation conditions were as follows: $A/V = 36.0/\mathrm{m}$ average UV intensity was 60000 lx, after 3h irradiation the colour removal of 20 mg/L methyl orange solution achieved 90%. This effect was attributed to the fact that the incident UV photons and active species consequently produced on catalyst surface increases with increasing of A/V ratio. Fig.5 showed the comparative result in both atmospheric condition sunny and cloudy. Their average UV isolation were 92600 lx and 45800 lx and corresponding

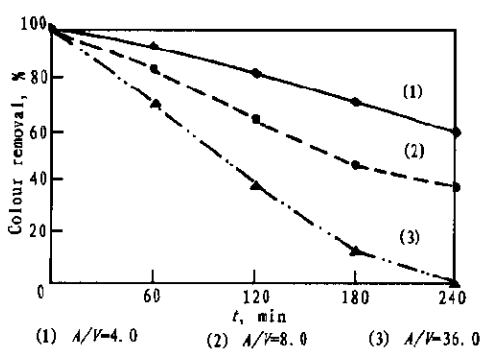

Fig.4 Effect of aperture to volume ratio on colour removal

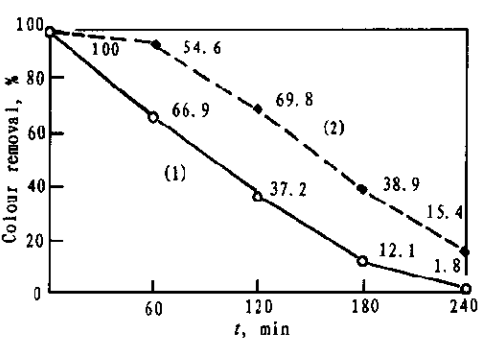

Fig.5 Effect of UV radiation intensity on colour removal

reaction rate constants were $1.38 \times 10^{-2}/\mathrm{min}$ and $0.62 \times 10^{-2}/\mathrm{min}$, respectively. It indicated that the photocatalytic decolorization rate constants was proportional to the solar incident UV intensity and it was proved the fact that the photocatalytic degradation of organics perform well under either sunny or cloudy atmospheric condition.

3.3 Solar flat plate photoreactor

The solar flat plate photocatalytic oxidation facility used for the present investigation is schematically shown in Fig.6 and Fig.7. It consists of a rectangular plastic flat plate having of 5 cm edge with dimension of $100 \times 150 \times 0.5$ cm^3 supported by a set of steel frame. A spray bar with evenly small holes, which serves to evenly distribute the solution, is set on the top of the flat plate. An effluent trough located near and under the reactor to collect the solution. Except the Teflon circulating pump, all of the system was fabricated from polyvinyl chloride plastic because they are inexpensive and inert to organic. The reactor faced due south and tilted at an angle of about 15 degree from the horizontal to insure the more direct light of solar insolation put in during test. The solar UV intensity was measured at same position by irradiance meter and recorded as same as

mentioned above. 20 mg/L methyl orange solution 10L and TiO_2 powder 10g were mixed and stored in the storage tank. A mixer was installed in the tank to insure the slurry mixed well. The fluid was pumped through flow meter, spray bar and into reactor, where it trickled along with the flat plate, then drain out from effluent trough back to tank. The experimental data showed in Fig. 8 clearly indicates reaction rate obviously increases with increasing the flow rate of solution system. It means that the reaction rate was dependent on the amount of irradiating solution within unit time.

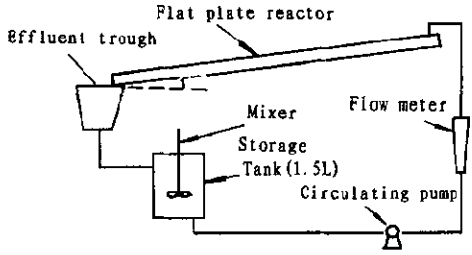

Fig. 6 Schematic diagram of solar flat plate photocatalytic oxidation facility

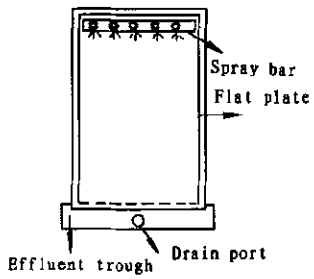

Fig. 7 Diagram of flat plate photoreactor

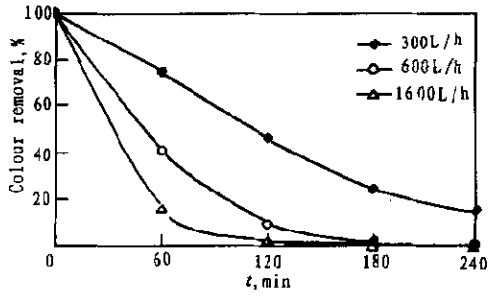

Fig. 8 Effect of flow rate on colour removal

4 Comparison of three reactors

4.1 Comparison of performance efficiency

The optimum experimental condition with three configuration reactors is listed in Table 1. In order to compare and assess synthetically them a new characteristic parameter K was offered. Which is defined as reaction rate constant at the same condition level; for certain test duration, incident UV intensity, catalyst dosing, irradiating area and initial concentration of methyl orange solution. It means that the performance efficient of reaction system is higher and it is advantage to destroy the contaminants if the K in this system is bigger. The experimental data clearly indicated that solar phtoreactor both shallow pond and flat plate performed better than annular-type irradiated by UV lamp. Those parameter K for both solar reactors are ten times greater than that for annular-type with UV lamp. It demonstrated that not only solar can alternate the UV lamp but also solar can perform better than lamp for contaminants degradation, in addition to the low running cost. The solar flat plate photoreactor can potentially accommodate to large volumetric throughput than shallow pond although its reaction rate constant is less than last one. In addition, the performance efficiency of flat plate will be further improved by increasing the flow rate of all system for large scale.

Table 1 Comparison of performance conditions for three configuration reactors

Reactor	Annular with lamp	Solar shallow pond	Solar flat plane
Light source	500W mercury lamp	Solar energy	Solar energy
Cooler	Quartz	no	no
Insolation intensity, I, W/m^2	996	20.12	26.93
Initial concentration of methyl orange, C_0, mg/L	20	20	20
Temperature, t, ℃	20	20	20
Catalyst amount, W_t, g/L	1.0	1.0	1.0
Solution volume, V, L	0.41	1.0	10.0
Irradiation area, A, m^2	3.7×10^{-2}	2.5×10^{-2}	1.45
Rate constant, k/min	6.96×10^{-2}	1.03×10^{-2}	3.20×10^{-2}
Characteristic parameter, $K\times10^4$ $K=\frac{C_0kV}{W_tIA}$, LW^{-1}min^{-1}	1.55×10^{-1}	4.10	1.64

4.2 Comparison of forthcoming application

It has been discussed by Matthews (Matthews, 1993) that the cost estimates with photocatalytic treatment of wastewater is similar to that with absorption using activated carbon. In the cost of photocatalytic treatment used electrically powered UV lamps mentioned above about 80% are those of the cost for electric power. In addition, the cost of reactor material is more expensive too and at least the part to be irradiated by UV lamp must be made of quarts. In contrast, for solar photoreactor the cost either for running or for construction will be saved obviously. It has been estimated also that the cost for solar shallow lagoon is about 1/3 of the using activated carbon. It was been proved that photocatalytic oxidation should be feasible to scale up for treatment technology on an industrial scale. Many organic compounds such as chlorophenol, herbicides, textile dye and surfactants are resistant to routine treatment or the effluent after biological treatment still contains unacceptable high levels of contaminants. In those cases, photocatalytic degradation is becoming highly attractive as an additional stage of treatment. Both photoreactors shallow pond and flat plate are good configurations for further application. Suggesting that it will be more efficient with combining the both advantages. It was been proved also that photocatalytic oxidation using solar energy mainly with auxiliary electric lamp should be feasible for wastewater treatment technology on industrial scale.

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