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OPTIMAL OPERATING CONDITIONS IN DESIGNING PHOTOCATALYTIC REACTOR FOR REMOVAL OF PHENOL FROM WASTEWATER

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ABSTRACT

The aim of this study is to review and evaluate the idea of treating phenol from wastewater by using titanium dioxide (TiO2) in a photocatalytic reactor to reach an optimal operating treatment condition. A brief review on photocatalytic lab-scale design plus the advantages of using TiO2 and its ability to remove phenol due to its unique chemical properties were studied. Previous photocatalytic experiments were discussed to obtain the ideal operating conditions for wastewater treatment. The best removal efficiency of phenol was found to be at pH 7 under UV irradiation lamps. Although catalyst dosage and initial feed concentrations are mostly preferred at higher values, the perfect dose was 0.2 wt% of TiO2. It was proven that the use of an aeration system would increase the efficiency by 50%.

Keywords: photoreactor, titanium dioxide catalyst, wastewater, treatment, phenol.

INTRODUCTION

Nowadays, treating industrial wastewater is a big challenge to many research centers around the world. Many industrial processes such as coal production, petroleum refineries, plastic manufacturing and coke oven process effluent a huge amount of phenolic industrial wastewater into oceans. Industrial wastewater contains numerous organic pollutants that are non-environmentally which are responsible for destructing marines' life. Essentially, phenol substance is the most common undesired material in the industrial wastewater since it is potentially toxic to both humans and microorganism life [1].

Recent studies showed that there is a potential solution to remove phenol by using titanium dioxide (TiO2) as a catalyst in a photocatalytic reactor in the presence of either Ultraviolet (UV) light or sunlight. Photocatalytic reactor is a reactor in which a chemical reaction can take place when there is enough light and catalyst at the same time. Thus, catalyst particles are able to absorb the photons energy and utilize this energy to initiate an electron for starting the photochemical reaction with an organic pollutant like phenol. By applying this process, we can easily decompose the poisonous phenol structure into harmless products [2]. The aim of the study is to design a more efficient photocatalytic reactor and analyze the performance of that reactor for degradation of phenol in industrial wastewater. The reactor performance is estimated by studying the effect of changing several parameters, such as pH, initial concentration of phenol, light intensity, catalyst dosage, aeration and flow rate recirculation, in order to achieve the optimal operating conditions [1].

PHOTOCATALYTIC REACTOR

The photocatalytic reactor is one of the reactor types that are usually simple to construct with the lowest operating cost compared to other alternatives. Add to that, photocatalytic reactor is very flexible to handle three-phase chemical reactions that occur due to the decomposition of phenol into clean water (H2O) and carbon dioxide (CO2) after exposing the wastewater-catalyst solution to light for a period of time [1]. The simplest lab-scale photocatalytic reactor is shown in Figure 1 [5]. Photocatalytic reactors use less amount of energy in UV-LEDs systems. The reason is that LED is identified to be very efficient as a light source for degradation of various chemicals in the presence of TiO2. Photoreactors were evaluated, in a lab-scale, to see the decrease in concentrations of several wastewater pollutants. The results were promising to most of the chemicals that have been tested. The lab-scale experiments showed that photocatalytic reactors are flexible to design, easy to operate, not costly and ideal for large-scale industrial wastewater treatment plants [4].

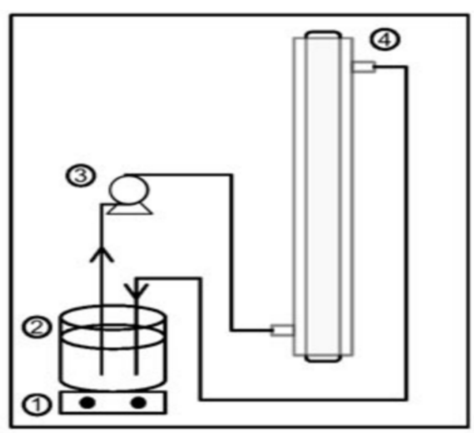

Figure-1. Lab-scale photocatalytic design, (1) magnetic stirrer, (2) vessel, (3) pump and (4) photocatalytic reactor [5].

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TITANIUM DIOXIDE CATALYST

There are many advantages of using TiO2 in photocatalytic reactor for degradation of phenol in industrial wastewater. According to recent studies, using TiO2 in photocatalytic reactor is the most common feasible, inexpensive, way to remove phenol as efficient as possible. Scientists found that the most convenient method to get rid of organic contaminants is by using TiO2 as a catalyst in degradation of phenolic wastewater; TiO2 is considered cheap, insoluble in water, harmless, resistant to most chemicals and highly active to light. Insolubility in water means that we do not have to use the same catalyst for one reaction only; but we have an excellent opportunity in getting the benefits of the same catalyst for many reactions in different treatment processes while it is unconsumed. TiO2 high sensitivity to light is another outstanding characteristic where it is vital in a photochemical reaction to have the ability to absorb the minimum amount of energy for initiation stage of the reaction [1]. The degradation efficiency of TiO2 can be increased by specific manipulations in the catalyst morphology or structure. For example, TiO2 that were doped with metals or non-metals were able to achieve better performance due to the reduction in the band gap needed for the reaction to occur. In other words, the reaction will initiate after absorbing visible light instead of UV only (Figure-2), reducing the waiting time to start the reaction and increasing the total reaction efficiency of TiO2 with the pollutant that is in interest [4].

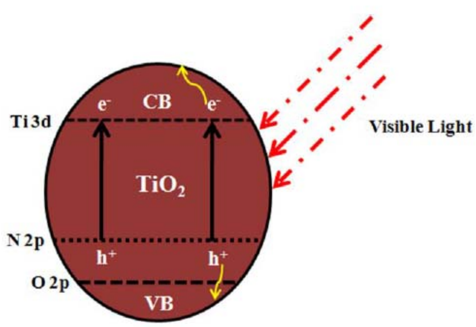

Figure-2. Doped TiO2 with reduced bands absorbing visible light.

Additionally, more pros are linked to the use of TiO2 in photocatalytic reactor. For instance, TiO2 catalyst required the least amount of band gap energy (eV) among other semiconductor materials, like ZnO and ZnS, in order to excite its valance electrons for initiating the photochemical reaction which is mainly related to increasing the consumption rate of phenol. Moreover, the energy source for initiation stage of such a photochemical reaction is infinite because the solar UV radiation comes either from a direct sunlight or UV lamps. Likewise, complete oxidation of organic pollutants in a few hours for ideal treatments that can neutralize harmful contaminations without leaving any hazardous residues is another foremost encouraging fact in choosing solar photocatalytic treatment technique for industrial wastewater [3]. Furthermore, optimal operating conditions such as temperature, pressure, pH and UV irradiation for TiO2 photocatalytic reactors are almost identified which make it easier for implementation phase. Even though there are other few factors that may disturb the reaction efficiency, for example: reaction contact time, it seems that very slight differences may only occur in the overall performance of the reactor [2].

EXPERIMENTAL ANALYSIS

Many research parameters were studied in the experimental laboratory work. Variations in these parameters were the guidelines in achieving the optimal operating conditions. For example, in Abhang's research, initial feed concentration of phenol, mass of catalyst, intensity of UV light and aeration system were all several factors to study in the laboratory work [1]. Similarly, pH of the feed solution was also considered to identify the effect of acidity or basicity on the degradation rate in Aljoubory's study. Aljoubory's research explored more about the influence of the flow rate recirculation in a continuous process reactor to realize the differences that may arise to the reaction rate performance [2]. Nevertheless, Priya's work investigated on materials of construction that were selected to avoid cracking of the internal reactor wall from the high reaction temperature that can reach up to 50ºC. Flexibility for designing, transparency to light and material cost were explored to choose the best choice for reactor [3].

Aljoubory's experiment started by collecting samples of wastewater that contains phenol from a petroleum refinery in Oman with different concentrations of 10, 30 and 50 mg/L. A previous installed photocatalytic reactor model had been used to do the lab experiments. First, batch reactor process was carried to find out most of the optimal operating conditions for phenol consumption. The reactants, wastewater and TiO2 catalyst, were charged into a container, well mixed and left for a period of time, about 1 to 2 hours, to react gradually. The idea of identifying the reaction optimum condition achieved by adjusting one parameter while all other factors were fixed in order to determine the impact of a particular factor at a time. After finishing with the batch process analysis, Aljoubory moved into further investigations through a continuous reactor process [2].

On the other hand, the experiment work of Abhang was nearly comparable to the prior study of Aljoubory in defining the ultimate operating conditions except that Abhang was more curious about the design fabrication considerations of the reactor. In fact, Abhang did not use an installed readily reactor model, instead he designed his own photocatalytic reactor before going on to the experimental part. The reactor type that Abhang was trying to build was a three-phase fluidized bed reactor which could mix solid, liquid and gas. It had a very low operation and construction cost, flexible to both liquid and

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solid phases and provide the most achievable contact time between TiO2 catalyst solid particles and phenolic wastewater. The reactor was designed in form of sandwich chambers to utilize UV light energy efficiently [1].

Plexi glass material used to construct the fabrication of Abhang's reactor since it has a good pressure durability and perfect optical properties. The outer dimensions of the reactor were 200 x 200 x 1000 mm. The reactor was mainly consisting of five vertical chambers and one common horizontal bottom chamber that connected the five chambers together. The middle vertical chamber was for the input flow while the outer vertical compartments, right and left, where for the output stream. The two remaining vertical sections, adjacent to the middle one, were utilized for the reaction and there were UV lamps adjusted on each of these two chambers. Further, the function of the bottom lateral chamber was to transfer the wastewater between vertical chambers when the photocatalytic reaction was already completed. Abhang designed the reactor with four lamps of 8 Watts, two on each side of the middle vertical chamber. Then, feed tank and pump to transfer the feed to the reactor were also included in the reactor design. Besides, an aeration system was installed to ensure a better distribution of the catalyst inside the reactor. The reaction period was around two hours under the room temperature (25ºC) and 1 atm. The reactor was tested with and without aeration fans to find out the major difference. Also, two different initial feed concentrations of phenol were taken for the experimentations, 4.98 and 1.93 gm/L. Likewise, three different catalyst loading were taken, 0.75, 1 and 4 gm/L. The light intensity effect measured by using 2, 4 and 8 Watts UV lamps. At last, UV and visible light experiments were carried out for more clarifications about the impact of using different sources of light [1].

RESULTS AND DISCUSSIONS

Aljoubory recognized the ideal conditions for operating the photocatalytic reactor to reach the maximum degradation efficiency. The best removal efficiency of phenol was found to be at pH 7 which is at neutral solution state, neither acidic nor basic. Besides, the effect of initial phenol concentration had the maximum efficiency for degradation of phenol at 25 mg/L (Figure-3). Moreover, 0.2 wt% was considered to be the perfect dosage of TiO2 catalyst for decomposing phenol. On top of that, an interesting fact was explored during the batch process experiments which stated that the degradation of phenol under sunlight was 13%, but utilizing UV irradiation lamps could increase the phenol degradation rate to 82%. In the continuous reactor process, two different flow rates of 1.2 and 1.6 L/min showed that the effect of flow rate recirculation on the reaction rate was preferred to be at lower value [2].

In Abhang experiment, the ideal operating conditions for higher consumption rate of phenol was determined as Aljoubory did before. The optimum initial phenol concentration of Abhang's experiment was at 4.98 gm/L with more than 40% of conversion in 10 minutes (Figure-4). An excellent result was found from using aeration system where it increased the degradation rate by 50%. In addition, the degradation of phenol increased by increasing the catalyst amount, but the increase was trivial because after particular amount of catalyst loading, the removal rate did not change with respect to time. The same observation was recorded in case of using various light intensity sources. Yet, the increase of degradation increased with increasing the light intensity by moving in time about 4% only, but it was estimated to increase further if we left the reaction for more time. The final Abhang's experiment, which was about UV and visible light, proved that visible light was possible to degrade the phenol but not as efficient as UV light that was generated from the four lamps. There was a rapid change in the decomposition rate when Abhang's utilized the UV light of those four lamps [1].

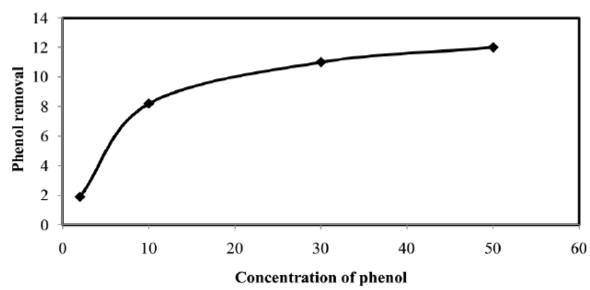

Figure-3. Degradation of phenol for different phenol concertation at 0.20 wt% of TiO2, 15W UV irradiation for 2 hr [2].

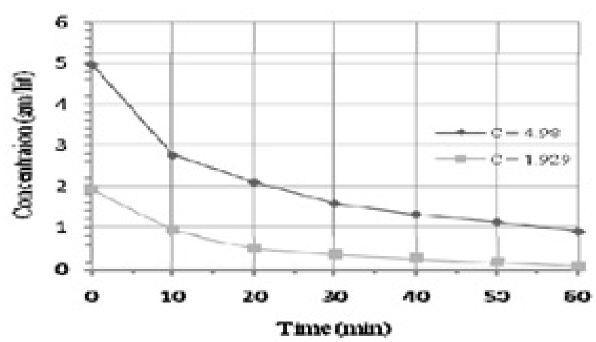

Figure-4. Degradation of phenol at different initial concentration; i) 4.98gm/lit, ii) 1.93 gm/lit [1].

By comparing both studies of Aljoubory and Abhang, we might conclude that there were many similarities between both results. For example, we could realize that both research studies agreed on the advantage of UV irradiation lamps that increased the reaction rate dramatically. Still, initial feed concentrations findings were not alike because Aljoubory used better set of concentrations with large differences, 10, 30 and 50 mg/L, while Abhang's set of initial phenol concentrations was only for two readings of 1.93 and 4.98 gm/L. Therefore, the ideal result of 25 mg/L, in Aljoubory's study, intended that the initial phenol concentration was preferred at a higher value, but there was a point, at 25 mg/L, in which the removal rate increase was worthless. To clarify this, we could infer that Abhang's optimum result at 4.98 gm/L might change to a higher point and confirm Aljoubory study, if Abhang had a more credible samples set. Nonetheless, the two experiments verified that using a higher amount of catalyst (TiO2) would enhance the photochemical reaction rate for having a more degradation rate.

CONCLUSIONS

In conclusion, designing a photochemical reactor for the removal of phenol is the most appropriate technique for industrial wastewater treatments. Aljoubory and Abhang research studies were successful in demonstrating the optimal operating conditions of a photocatalytic reactor by using TiO2 and UV light to reach the maximum efficiency of phenol removal. Generally, utilizing UV lamps light and supplying an aeration fans system will increase the degradation rate of phenol by at least 50%. Moreover, using a continuous reactor with low feed flow rate has a better phenol decomposition rate than a batch reactor. Catalyst dosage and initial feed concentrations are mostly preferred at higher values, but at a certain point, the increase in the degradation rate seems to be worthless. Hence, future studies should consider samples sets to be in larger range difference to accomplish results that are more accurate. Finally, as long as phenolic wastewater is increasing day after day due to the high demand on countless industrial products, scientists should take an action as soon as possible by applying this substantial process on a large scale in petrochemical industries to protect the environment from a prospective danger.

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