Basic Design of a Fluidized Bed Reactor for Wastewater Treatment Using Fenton Oxidation

Farhana Tisa, Abdul Aziz Abdul Raman, and Wan Mohd Ashri Wan Daud

***Abstract*—Fluidized bed reactor (FBR) can be an efficient alternative solution in advanced water treatment processes. Fenton oxidation is popular among other advanced oxidation processes. FBR-Fenton process can reduce production of sludge in water treatment and also offers lower hydraulic retention time compared to other biological and chemical processes. This research work is an attempt to develop basic steps to design this FBR. A practical design protocol of the feature for treating phenolic water was developed. Detailed design parameter studies which include different correlations for calculating the required design parameters. The design calculations have been done based on literature and some collective assumptions. From this work it can be summarized that, calculated flow rate for working fluid was found to be 1.4 l /min or more for complete fluidization, where the settling velocity of the particle was found to be 0.0365 m/s and the calculated Reynolds number implied that, the fluidization to be a laminar fluidization.**

***Index Terms*—Fluidized bed, water treatment, design.**

I. Introduction

Fluidized bed reactor is widely applied in many industries for various applications recently. It has been found promising to use fluidized bed reactor for water treatment procedures. When the conventional treatment procedures failed to remove recalcitrant compounds in waste water, advanced oxidation processes came as a foremost choice by the researchers. However, AOPs are yet not without limitations. Studies reveal that an effective contacting device system can increase the potential of advanced oxidation systems. Some authors have used Fluidized bed reactor with conventional treatments procedures, such as, activated carbon [1], [2], anaerobic treatment [2], [3] and also electrochemical procedures [4]. Conventional treatment posses some limitations likes, increase in toxicity level [5], more power consumption, plugging and clogging [6] and less degradation efficiency [7]. AOP merge with FBR can be more potential in pollutant abatement. One of the advanced technology that can be highlighted as the most efficient for recalcitrant water treatment is Fenton oxidation. Initiatives have been done on using FBR with Fenton procedures, such as photo-Fenton oxidation in fluidized bed reactor [8], heterogeneous Fenton oxidation [9], homogeneous fluidized bed Fenton process [10], [11]. Fluidized bed reactor adds some advantages to the Fenton procedures such as, uniform heat and mass transfer, reduction of sludge production, less oxidant usage and more users friendly. Although fluidized bed Fenton have been studied much, few or no significant studies have been done on the studying the design procedures for FBR-Fenton.

Fluidized Bed reactor is a process which is now widely applied in many industrial applications. In recent studies it is evident that, fluidized bed reactors can also be an attractive procedure for treating polluted water. Waste water that is generated from many industries is highly recalcitrant and is threatening to environmental ecology and human lives. Biological and chemical processes have failed to convert the contaminants fully as, biological and chemical processes and degrade up to 60% of the recalcitrant components and in addition they require larger operation area and more chemical processes to reduce the sludge. Advanced treatment technologies that involve highly oxidizing compounds like OH has overcome the limitations of biological and chemical treatment procedures. Through review it can be said Fenton process is more productive when the reaction gets a efficient reaction platform, that is Fluidized bed reactor. Fluidized bed reactors have been used and design for different physical and chemical process for example, catalytic cracking, fluid transportation and drying. Due to increasing importance of treatment of wastewater in FBR critical examinations of the parameters that possesses the design and operation of the treatment procedure have been done on this paper. The methodology section provides the design strategy involving hydrodynamics, thermal and kinetic nature. Essential recommendation towards design calculation has been summarized in the result section. This work will focus on design of the FBR for pollutant treatment.

II. Pollutant Degradation in Fluidized Bed Reactors

Fluidized bed reactors can be considered as an improvement over the traditional water treatment methods associated with Fenton oxidation for pollutant degradation. Operation of FBR has confirmed many advantages that include high degradation efficiency, lesser reaction time and better catalyst re-circulation. Technical knowledge about design and operation of FBR is not widely available. Also little has been done in the field of designing FBRs. Table I represents studied subjects on FBRs for pollutant degradation. Degradation of pollutant in fluidized bed reactor involves chemical reactions and liquid-solid-gas flow structures.

Manuscript received November 18, 2013; revised February 13, 2014. This work was supported in part by the University of Malaya High Impact Research Grant (HIR-MOHE- D000038-16001) from the Ministry of Higher Education Malaysia and University of Malaya.

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TABLE I: FBR APPLICATION IN ORGANIC POLLUTANT DEGRADATION

Pollutant degraded	Area of Study	Reference
2,4 dicholophenol	Design of experiments	[11]
Phenol	Mineralization and kinetics	[8]
TFT-LCD wastewater containing ethanolamin	Optimization	[12]
Aniline	Comparision between Electro-Fenton and FBR-Fenton	[13]
Nitrobenzene	Kinetics	[14]
Dyes and textile waste water	Oxidation path	[15], [16]
		[1]
Chlorophenol	Magnetically stabilized FBR	[17]
Sanitary landfill leachate	Anaerobic treatment	[18]
Methyl orange	Effect of operating parameters	[19]
Benzoic acid	Kinetics	[10]
RB5, RO6, RB2	effect of operating parameters	[16]
Acetaminophen	Kinetics	[20]
Tetrafluro propanol	Mineralization	[21]

A. General Design Strategy for FBR-Fenton

Since water treatment through fluidized bed reactor will contain a catalyst and beads bed in consistent amount according to the pollutant feed, the design need to account for one specific condition for calculation. The strategy of Fig. 1 therefore sidesteps for specific considerations. The different steps are discussed hereafter. To predict the behavior of a chemical reactor requires information on the hydrodynamics, stoichiometry, thermodynamics, heat and mass transfer, reaction rates, and lastly, flow or contacting pattern of materials in the reactor.

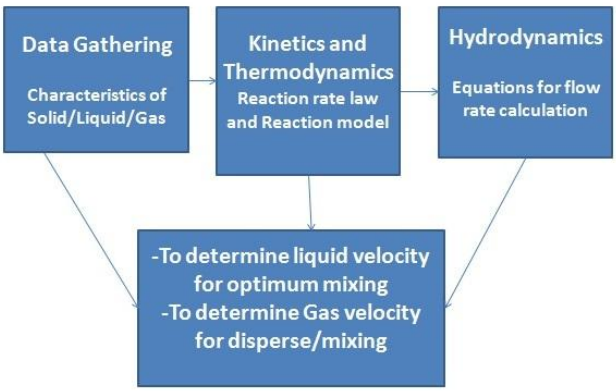

Fig. 1. Proposed design steps involved in the FBR design.

III. DATA GATHERING

A. Properties of Pollutant and Reactants

As previously highlighted, FBR-Fenton promises/ guarantees efficient pollutant degradation of different pollutants [12], [13]. Table II represents different pollutant degraded with FBR-Fenton procedure. The properties of the pollutants are important to determine the design steps. These properties include the concentration of the pollutant, catalyst or carrier density and particle size, air/gas density and viscosity. Particle characteristics include particle size distribution and average size, bulk density. The reaction kinetics can be determined by literature data and experimental work. In our transition fluidized bed particle size in the bed material are in the range of 0.5 to 2 mm. At the start up the bed the bed consists of catalyst (ρ_p= 4580kg/m^3) and glass beads (ρ_p= 1600kg/m^3). The bed characteristics rather relate to glass beads than to goethite catalyst. The dominant parameter in this fluidized bed reactor is the liquid velocity. Table I represents the variety of studies done on some pollutant degradation on fluidized bed reactor.

Optimum mixing in the bed is achieved within specific velocity limits that are function of the particle size of bed material [22]. This emphasizes that, bed properties are one of the vital properties which is bound to be known (for example, the target pollutant viscosity and density). On applying homogeneous Fenton procedure, glass beads have been used in FBRs [11], [16], [23], thus, in that case, particle size and density of the glass beads are important. When heterogeneous catalysis will be used for treatment [10], [19], the catalyst size and density should be on knowledge. When it is a mixture of pollutant in water, the average density of the polluted water must be known.

TABLE II: SOME SUBJECTED DESIGN PARAMETERS IN FBR-AOP PROCESSES

Targeted pollutant	Ref	Chemical	Properties	Subjected design parameters
2,4 -Dichlorophenl	[11]	Water	Density @ 30°C, 1000 kg/m^3 Viscosity @ 30°C, 0.7879×10^{-3} Pa.s	, U_{mf}, U_f, U_t
		Hydrogen Peroxide	Amt, 100 g	
		Glass beads	Particle dia, 0.84-2.00 mm Density, 1600 kg/m^3	
		Ferrous sulphate	$FeSO_4$	
		2,4 DCP	$C_6H_4Cl_2O$ Density @ 30 C, 1380 kg/m^3	
Benzoic Acid	[24]	Water	Density @ 30°C, 1000 kg/m^3 Viscosity @ 30°C, 0.7879×10^{-3} Pa.s	, U_{mf}, U_f U_t
		Hydrogen Peroxide	H_2O_2, FeOOH Amount, 80 gm Bulk density, 1110 kg/m^3 Average particle size, 0.564 mm Specific surface area, 48.3 m^2/g	
		Lepidocroci te Hydrogen Peroxide Glass beads Ferrous chloride	H_2O_2 SiO_2 Particle dia, 2.00-4.00 mm Density, 1600 kg/m^3 $FeCl_2$	
	[4]	Crushed Activated Carbon P-nitrophen	Particle dia , 30-35 mesh Density, 2g/l waste water	, U_{mf}, U_f, U_t

P-nitrophenol (PNP)		ol	$C_6H_5NO_3$	
		Water	Density @ 30˚C, 1000 kg/m^3 Viscosity @ 30˚C, 0.7879×10^{-3} Pa.s	
Methyl orange	[19]	Methyl orange	$C_{14}H_{14}N_3NaO_3S$ Density, 1280 kg/m3	, U_{mf}
		TiO_2 powder	Particle dia, 21 nm Density @ 20˚C, 3890 kg/m^3	
		Air phase/ Gas phase	Density, 1.0241 kg/m^3	
			Viscosity, 18.6×10^{-6} Pa.s	
Styrene	[25]	Styrene	C_8H_8 Density, 909.00 kg/m ^{3}	, U_{mf}
		Catalyst named SGP251CC	Particle size, 100-1000 um Assumed mean particle size, 400 um Density, 700 kg/m^3	
Acetaminophen (ACT)	[20]	Acetaminophen		, U_{mf}, U_f, U_t
		Hydrogen peroxide	H_2O_2	
		Glass beads and SiO_2	Particle dia , 2-4 mm and 0.5 mm Density, 1600 kg/m^3	
		Ferrous sulphate	$FeSO_4$	
Textile waste water	[15]	Ferrous sulphate hepta hydrate Glass beads and SiO_2 Hydrogen peroxide	$FeSO_4.7H_2O$ Particle dia , 2-4 mm and 0.5 mm Density, 1600 kg/m^3 H_2O_2	, U_{mf}, U_f, U_t
RB5, RO16, RB2	[16]	Ferrous sulphate hepta hydrate	$FeSO_4.7H_2O$	, U_{mf}, U_f, U_t
		Glass beads and SiO_2	Particle dia , 2-4 mm and 0.5 mm Density, 1600 kg/m^3	
		Hydrogen peroxide	H_2O_2	

* =void fraction of bed, U_{mf}=minimum fluidization velocity, U_f= maximum fluidization velocity, U_t= terminal velocity.

B. Design Parameters

Design parameters mean the parameters to be considered for analysis and calculation in case of designing the Fluidized bed reactor for the treatment. For industrial application of fluidized bed reactor the hydrodynamics should be known. The Fluidized Bed reactor design should be made according to information available in the literature. The formulas for the design parameters are to be selected from vast literature available on researches in fluidized bed reactors and the study of fluidization profiles. Table II also gives us an insight on the possible parameters to be taken on account for design purpose. The basic design calculations for this FBR-Fenton were done based on the works of Leva (1959), J. P. Zhang *et al*. (1998) and R. K. Singh and G. K. Roy (2005).

C. Design Calculations

1) Mean diameter of the bed particles

Our purpose is waste water treatment and this involves multiple size catalyst in the system. Fluidization characteristics depend on the composition of the mixture of different particle size at varying composition. Therefore, the bed voidage , minimum fluidization velocity and fixed bed pressure drop have dependence on the average particle diameter and mass fraction of the fines in the mixture [26]. Supposing if, we have particle size of dp_1, dp_2 and dp_3 of same density and if, the composition of the mixture is a_1:a_2:a_3, generally the equation for mean particle diameter would be

$$d_p = \frac{1}{\sum_{i=1}^{n}\left(\frac{f_1}{d_{p1}}+\frac{f_2}{d_{p2}}+\frac{f_3}{d_{p3}}\right)}$$

(f_i indicates the fraction of i^{th} component).

2) Sphericity of the particle

Sphericity is the measure of particles where, the particles are not ideal in both shape and roughness (Wei and Yu, 1994). It is the measure of a particle's nonideality in both shape and roughness. It is calculated by visualizing a sphere whose volume is equal to the particles and dividing the surface area of this sphere by the actually measured surface area of the particle. The average sphericity for the particle mixture can be calculated by two different methods. First by the use of the correlation of Narsimhan [27] for mono disperse particles. For binary and ternary mixtures the equation can be written as

$$\frac{1-\in}{\phi_s} = 0.231\log d_{psm} + 1.417$$

where $d_{p,sm}$ is the average particle diameter in feet, ε is the void fraction and φ_s is the spericity. In the second method the average sphericity has been calculated from the sphericity data of irregular particles of dolomite of different sizes reported by Singh [28]. The average sphericity can be taken as the mass mean sphericity and can be calculated using the following equation, [29].

$$\phi_s = \sum_i x_i \phi_{si}$$

Normal measured values for a typical granular solid range from 0.5 to 1, with 0.6 being a choice for every round shaped particle.

3) Void fraction of the bed

Before determining the minimum fluidization velocity of the reactor the void fraction, e_{mf} of the bedparticles should be calculated. In our three phase fluidization upward liquid flow will fluidize the bed particles. Our fluid bed consists of goethite catalyst and glass beads. We will consider the mean particle diameter and mean glass bead density as the solid particle density for this calculation. This e_{mf} is the void fraction at the point of the minimum fluidization.

In 1950 Borwnell *et al.* obtained a graphical correlation, corresponding to the conditions of low, medium and high bed densities by studying the variation of bed voidage as a function of particle shape for different bed densities. Table III represents some correlations found in literature on calculation of void fraction.

TABLE III: CORRELATIONS FOR CALCULATION OF VOID FRACTION

Correlation and Conditions for applying	Ref.
$\in_{mf} = 0.586^{-0.7}\left(\frac{\mu^2}{\rho_f \eta d_p{}^3}\right)^{0.029}\left(\frac{\rho_f}{\rho_c}\right)^{0.021}$ or $\in_{mf} = 0.586^{-0.7}\left(\frac{\mu^2}{\rho_f \eta d_p{}^3}\right)^{0.029}\left(\frac{\rho_f}{\rho_p}\right)^{0.021}$ Where, $A_r = \rho_f\left(\rho_f - \rho_c\right) g \frac{d_p{}^3}{\mu_f{}^2}$	[30]
-for liquid-solid or gas-solid fluidization $\in_s = \frac{M_v}{\frac{\pi}{4D_f 2\rho_s H_s}}$ -at minimum fluidization velocity -with minimum entrainment of solids -Most of the bed material is stable in this three phase fluidization -where gas fluidization is stopped with liquid velocity decreasing	[31]

* mf is the void fraction at minimum fluidization condition, μ is the viscosity of the fluid, ρ_f is the density of fluid, ρ_p is the density of particle, ρ_c is the density of catalyst. s is the void fraction when the bed is stable, H_s is the height of bed when at stable condition, M_v is the volumetric flowrate, D_f diameter of particle.

4) Minimum fluidization velocity, U_{mf}

Most of the researches on FBR-Fenton procedure have been practiced on a batch fluidized bed reactor. There can be various options of which fluidization procedure might be followed for waste water treatment. For instance, Liquid-solid circulating fluidized bed can be chosen considering higher strength catalyst particle [32]. Conventional liquid–solid fluidization was studied intensively during the fifties.

For pollutant treatment procedure the hydrodynamics of liquid-soild fluidization and liquid-solid-gas fluidization can bring the solution for design purpose. It has been considered that liquid–solid fluidization is a uniformly dispersed homogeneous fluidization, with or without external particle circulation and regardless of the fluidization regime. This assumption of homogeneous behavior for the liquid–solid fluidization systems considers the liquid–solid fluidization as an ideal system and forms the basis of Richardson and Zaki and Kwauk's work [31].

Minimum fluidization velocity is for fluidizing the bed particles from the bed. It is the velocity required to begin the fluidization at which the weight of particles gravitational force equals the drag on the particles from the rising gas [33]. The ergun equation known for calculating minimum fluidization velocity requires the value of void fraction which is simplified by Wen and Yu (1966). For a range of particle types and sizes, Wen and Yu (1966) developed an expression for the minimum fluidization velocity. Table IV highlights some correlations literature on calculation of minimum fluidization velocity.

TABLE IV: CORRELATIONS FOR CALCULATION OF MINIMUM FLUIDIZATION VELOCITY

Correlations	Reference
$U_{mf} = 7.90\times10^{-3} d_p{}^{1.82}(\rho_s - \rho_f)^{0.94}\mu_f{}^{-0.88}$ -assuming $(\phi \in_{mf})^{-1} \approx 14$ & $\frac{(1-\in_{mf})}{\phi^2 \in_{mf}{}^3} \approx 11$	[32]
$\mathrm{R}_{elmf} = \sqrt{\left(33.72 + 0.0404 A_{rl}(1-\alpha_{mf})^3)\right)} - 33.7$ -Minimum liquid-solid fluidization -liquid phase Archimedes number , $A_{rl} = \rho_l\left(\rho_f - \rho_l\right) g \frac{d_p{}^3}{\mu_l{}^2}$ -Three phase fluidization involving Newtonian fluids -Equates the liquid-buoyed weight of solids per unit bed volume to the frictional pressure gradient given by Ergun packed bed equation -In the absence of gas flow i.e., for $\alpha_{mf} = 0$ -For three phase fluidization estimated value of α_{mf} is required. Which is given by Yang *et al.* [35] -for $x = \frac{U_g}{U_g + U_l} \leq 0.93$, where, U_g is gas velocity, U_l is liquid velocity.	[34]
$\mathrm{R}_{egmf} = \sqrt{\left(33.72^2 + 0.0404 A_{rlg})\right)} - 33.7$ -In the case where the solids are submerged by liquid and wetted by liquid -thus the solids will be buoyed by the liquid -the buoyancy term $\left(\rho_s - \rho_l\right) g$ In the gas phase Archimedes number is replaced by $\left(\rho_f - \rho_g\right) g$ -So the A_{rlg} is the gas-phase Archimedes number with liquid buoyed solids given by $A_{r\lg} = \rho_l\left(\rho_f - \rho_l\right) g \frac{d_p{}^3}{\mu_l{}^2}$	
$\mathrm{R}_{emf} = \sqrt{\left(25.25^2 + 0.03841 A_r)\right)} - 25.46$	[36]
$\mathrm{R}_{emf} = \sqrt{\left[\left(42.857\frac{C1}{C2}\right)^2 + \frac{A_r}{1.75C1})\right]} - 42.857\frac{C1}{C2}$ -Value $\in_{mf}$ is a function of φ at constant values of $C1$ and $C2$. -$C1$ and $C2$ are different for different correlations proposed by authors.	
$u_{mf} = \frac{\mu_f}{d_p \rho_f}\sqrt{\left(25.25^2 + 0.0651 A_r)\right)} - 25.25$ - Superficial velocity at minimum fluidization	[37]

*R_{egmf} is the Reynolds number for gas flowrate at minimum fluidization condition, A_{rlg} is the Archimides number for liquid and gas fluidization.

5) Maximum fluidization velocity, U_f and terminal settling velocity, U_t

If gas or liquid velocity is increased to a sufficient limit, that the drag on every particle will surpass the gravitational force on the particles. This velocity if called Maximum fluidization velocity. Maximum fluidization is important parameter to know for avoiding particle entrainment. The operating fluidization velocity depends on the maximum fluidization velocity too. Correlations for calculating maximum fluidization velocity can be found from literature and are presented on Table V.

TABLE V: CORRELATIONS FOR CALCULATION OF MAXIMUM FLUIDIZATION VELOCITYS

Correlation	Conditions for applying	Reference
$U_{fl} = \left(\dfrac{1.78 \times 10^{-2} \eta^2}{\rho_f \mu} \right)^{1/3} d_p$	- for Re >100 - fluid can be either gas or liquid	[38]
$U_t = \left[\dfrac{4gd_p(\rho_f - \rho_p)}{3\rho_f C_D} \right]^{1/2}$	-for different range of Re -C_D changes with different range of Reynolds number	[39]

*U_{fl} is the Maximum fluidization velocity for liquid flowrate, C_D is the Drag coefficient.

IV. RESULTS

This FBR design is for water treatment process, so we should know the characteristics of the chemicals and catalysts to be used in this process. Synthetic phenolic water was used as our liquid phase in this FBR and Air was used as the gas phase. And bed will consist of Goethite catalyst and glass beads. The diameter of the bed particles ranges from 1 mm to 3 mm. For our calculation purpose, density of liquid phase was considered to be same as water density and density of the bed particles were considered to be same as the glass beads as the amount of Goethite is comparatively small. The characteristic properties have been presented in Table VI.

TABLE VI: CHARACTERISTIC PROPERTIES FOR DESIGN PURPOSE

Liquid Phase				
	Amount	Density @ 30˚C	Viscosity @ 30˚C	Diameter (mm)
Water	1 liter	1000kg/m^3	0.7879× 10^{-3}Pa.s	-
phenol	100mg/liter	-	-	-
H_2O_2	30-100 mg/liter	-	-	-
Solid Phase				
Goethite catalyst	2 gm / l	4580kg/m^3	-	1.0
Glass beads	30 gm / l	1600kg/m^3	-	2.0
Gas phase				
Air		1.0241kg/m^3	18.6 ×10^{-6} Pa.s	-

The Fluidized Bed reactor design was made according to information available in the literature with innovative reforms implemented by research. Conventional formula for the calculation of the volume (V) and cross sectional area (Ac) of a cylinder was used. The calculated results for our featured FBR are summarized below in Table VII.

TABLE VII: OBTAINED RESULTS FOR FINAL DESIGN

Design parameter	Calculated result	Ref. of chosen formula
Volume of the reactor, *V*	2693.922 cm^3	General formula
Cross sectional area, *Ac*	38.4846 cm^2	General formula
Reynolds number, *Re*	173 (By iteration)	[35]
Void fraction, $\in_{mf}$	0.59893	
Minimum fluidization velocity, U_{mf}	0.02128 m/s	[33]
Terminal settling velocity, U_t	0.0365 m/s	[39]
Maximum fluidization Velocity, U_f	0.1843 m/s	[29]

The calculated values of the parameters are implemented in our fluidized bed reactor of 2.6 liter working volume. The minimum flow rate for liquid is 0.1617 liter/ min obtained from the calculated minimum fluidization velocity and assuming outlet pipe diameter of ½ inch. For turbulent mixing of the particles the calculated flowrate of liquid is equal to or higher than 1.4 liter/min. Calculation of flow rates for other Fenton procedures with varying catalyst characteristics would be different.

V. CONCLUSION

This research contains descriptive steps and calculation for designing this particular FBR which is a potential contribution to water treatment technologies. Literature has been summarized in this paper for clear understanding. Calculations are self explaining and can be followed for other specific FBR design purpose. The performance of the FBR is to be evaluated for treatment of phenolic water (<200ppm). Simulation work is on-going to predict the performance inside the reactor as well. Geometric changes (such as baffles) can be introduced to see the affect on pollutant abatement as future contribution. Additionally, economical feasibility study can be another part for future extension of this work.

ACKNOWLEDGMENT

The Authors thank financial support from University of Malaya High Impact Research Grant (HIR-MOHE-D000038-16001) from the Ministry of Higher Education Malaysia and University of Malaya.

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