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Analyzing Flow Characteristics and Influence of Biological Growth on Dispersion in Aerated Submerged Fixed-Film Reactors (ASFFR)

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ABSTRACT

The Aerated Fixed Activated Sludge System is one of the biological systems used to treat different types of wastewater containing organic substances. This paper presents the results of the preliminary phase of a study to determine the performance pattern of such a system treating petrochemical wastewater on a pilot scale. As the hydraulic characteristics of such systems are important factors affecting the behaviour, design and interpretation of data from the reactor, the hydraulic regime of the system was determined using a pulse input of Rhodamine B into the system. Various air supply and water flows were used as independent variables during the tracer study. Experimental data in 16 different conditions
were collected and dispersion number (d/ul) in each condition was determined using a computer program which was developed in this research. Furthermore, the statistical patterns were used to evaluate the fit of data in each condition with the ideal completely-mixed model. The results showed that, in a wide range of air supply and water flows, the completely mixed condition is achievable in this system; biological growth of film at different hydraulic loading rates did not change the pattern of mixing significantly. The content of this article is so organized that the complete methodology and computational approaches for performing flow pattern characterization in water and wastewater treatment systems are easily available.

Key Words: fixed activated sludge, aerated submerged fixed-film reactors, hydraulic regime, dispersion number, mixing

INTRODUCTION

Aerobic biological wastewater treatment processes are extensively used for removing organic substances. Aerated Fixed Activated Sludge, also known as Aerated Submerged Fixed-Film Reactor (ASFFR) in recent publications, has been used for more than 60 years, and now is an alternative for treating various kinds of industrial wastewaters including petrochemical industries.

Stability, high efficiency in COD removal, long cell residence time, independence of the system to the performance of secondary settling tank, short-term and simple start up and ease of operation due to omitting a sludge recirculation line, are the special specifications of this system which make wastewater treatment simple.

As uniformity and effective contact between substrate and biomass in such a system play an important role in its performance and behaviour, it is necessary to determine the hydraulic characteristics in practice. It should be noted that the completely mixed condition is preferred in order to take the best advantage of the total area of packed media in practice. Furthermore, many factors such as water flow, air supply, shape and morphological characteristics of packed media and filter porosity also affect the flow pattern in the system. Therefore, before starting up such biological reactors, tracer studies should be performed to determine the status of the hydraulic regime.

Tracer studies should be based on theoretical principles and also definite procedures in order to make the results of different tests comparable. After collecting data of tracer study in a reactor, an analytical approach is required for interpretation. Here the principles of two different methods that are used in this research are briefly discussed.
Method 1

Determination of Dispersion Number (d)

One of the popular approaches for the determination of hydraulic regime in a reactor, is calculating dispersion number (d). Dispersion number in an ASFFR may be defined as below.

\[ d = \frac{D}{L} \]  (1)

d = Dispersion number of reactor (dimensionless)

\[ D = \text{Upflow Dispersion Coefficient} \left( \frac{L^2}{T} \right) \]

\[ u = \text{Mean Flow Velocity} \left( \frac{L}{T} \right) \]

\[ L = \text{Height of the Reactor (L)} \]

In practice, Dispersion Number can be calculated through a tracer study. In this approach an appropriate tracer such as Rhodamine-B is injected either in a pulse or continuously. After injection, concentration of tracer in the outlet of the system is measured periodically. Based on concentration data at different times, the normalized variance of data distribution may be calculated as below:

\[ \bar{\varepsilon} = \frac{\sum t_i \varepsilon_i}{\sum \varepsilon_i} \]  (1)

\[ \sigma^2 = (\frac{\sum t_i^2 \varepsilon_i^2}{\sum \varepsilon_i^2}) - \bar{\varepsilon}^2 \]  (2)

\[ \sigma_{g}^2 = (\sigma^2 - \bar{\varepsilon}^2) = 2 \left( \frac{D}{uL} \right) - 2 \left( \frac{D}{uL} \right)^2 (1 - e^{-\frac{uL}{D}}) \]  (3)
Where:

\( t_i = \) elapsed time

\( c_i = \) tracer concentration at \( t_i \)

\( \bar{t} = \) mean residence time (time to the centroid of the distribution)

\( \sigma^2 = \) variance

\( \sigma^2_0 = \) normalized variance (dimensionless)

The variance and Dispersion Number for a reactor are calculated from the effluent concentration-time data from a pulse input. After the dye injection at the inlet of the reactor, output samples are collected at time intervals from 0.5 min to several minutes. The shape of the residence time distribution is determined by graphing the concentration versus time.

The dispersion number (D/ul) can be computed using Eq. 3 through a trial and error procedure. In this research a computer program has been developed for determining dispersion number and calculating the parameters required for graphing time distribution curves. This program is a FOXPRO routine and source code is presented in Table 1. Each dispersion number then should be compared with typical ones according to (Viessman, 1990) in order to determine the hydraulic regime of the reactor.

**Table 1 - Computer Programme for Computing Dispersion Number Using Tracer Test Data.**

```
Set Talk Off

Set Echo Off

set dele on

CLEAR ALL
```
CLEAR

STORE SPACE(8) TO NAME

@2,2 SAY "ENTER THE DATA FILE:" GET NAME

READ

IF !used("&NAME")

Select 0

use &NAME

ELSE

Select &NAME

ENDIF

dbfname=dbf()

Clear

STORE 0 TO Ndata,C0,TR

@ 7,5 SAY " Tracer Concentration:" GET C0 Picture "999999.99"

@ 8,5 SAY " Theoretical Detention Time:" GET TR Picture "9999999.99"

READ

Count all to NUM

GO TOP
FOR i=1 To NUM

Replace CAL_T_TR WITH T/TR ;
CAL_C_C0 WITH C/C0 ;
THEO_C_C0 WITH EXP(-T/TR) ;
TC WITH T* C ;
T2C WITH T^2*C

SKIP

ENDFOR

BROWS

SUM C To Sigma_C
SUM TC TO Sigma_TC
SUM T2C TO Sigma_T2C

TBAR= Sigma_TC/Sigma_C

VARIANCE= (Sigma_T2C/Sigma_C)-(TBAR^2)

Norm_var= Variance/(TBAR^2)

D_UL=TRY(Norm_var)

Set print On

Set Printer to DULOUT.TXT
Count all to NUM

GO TOP

? "" ORDER OF VARIABLES FROM LEFT TO RIGHT:"

?""TIME,CONCENTRATION,CALCULATED T/TR,CALCULATED C/C0,THEORITICAL C/C0,T/TBAR,TC,T2C"

?

FOR i=1 To NUM

? ALLTRIM(STR(T,12,4))+" "+ALLTRIM(STR(C,12,2))+" "+ALLTRIM(STR(CAL_T_TR,12,6))+" "+

ALLTRIM(STR(CAL_C_C0,12,6))+" "+ALLTRIM(STR(THEO_C_C0,12,6))+" "+

ALLTRIM(STR(T/TBAR,9,3))+" "+ALLTRIM(STR(TC,12,2))+" "+

ALLTRIM(STR(T2C,12,2))

SKIP

ENDFOR

?

? dbfname

? SPACE(5)+'""Initial Concentration:"'+STR(C0,14,2)

? SPACE(5)+'""Theoritical Detention Time :"'+STR(TR,14,2)

? SPACE(5)+'""Sigma C:"'+STR(Sigma_C,14,2)
Set print OFF

Set Printer to

CLEAR ALL

CLEAR

MODI FILE DULOUT.TXT

FUNCTION TRY

PARAMETERS CONTROL

PUBLIC CASE

JUMP=0.00001

DO While .T.

? CASE,",CONTROL","",JUMP
WAIT

CASE=(2*JUMP)-(2*JUMP^2)*(1-EXP(-1/JUMP))

IF (CASE<=0)

_OUTPUT=OPTIMIZ(JUMP,CONTROL)

Return(_OUTPUT)

* JUMP=JUMP/10

* EXIT

ENDIF

IF (CASE<=CONTROL)

JUMP=JUMP*10

ELSE

EXIT

ENDIF

ENDDO

INITIAL=JUMP/10

FINAL=JUMP

GAM=INITIAL/100000

FOR I=INITIAL TO FINAL STEP GAM

CASE=(2*I)-(2*I^2)*(1-EXP(-1/I))

"CASE","CONTROL",INITIAL,FINAL

*WAIT

IF ABS( CASE-CONTROL )<=0.0001

Return(I)

ENDIF

ENDFOR

FUNCTION OPTIMIZ

PARAMETER JUMP,CONTROL

INITIAL=JUMP/100

FINAL=INITIAL*10

GAM=INITIAL/100000

Do While .T.

FOR I=INITIAL TO FINAL STEP GAM

CASE=(2*I)-(2*I^2)*(1-EXP(-1/I))

IF ABS( CASE-CONTROL )<=0.0001

Return(I)

ENDIF

ENDFOR

ENDFOR
INITIAL=FINAL

FINAL=INITIAL*10

GAM=INITIAL/100000

LOOP

ENDDO

Method 2:

Fit of collected data in a Tracer study with Completely Mixed Model

Theoretically the effluent concentration of tracer with a steady-state flow and completely mixed regime in the reactor, can be formulated as below:

\[ C = C_0 e^{-\frac{T}{T_r}} \] 4)

Where:

\[ C = \text{effluent tracer concentration of reactor} \]

\[ C_0 = \text{initial tracer concentration at the beginning} \]

of the test.

\[ T = \text{elapsed time} \]
\[ T_r = \text{Theoretical Hydraulic detention time} \]

Converting the Eq. 4 to a linear equation is simply performed as below:

\[
\ln \frac{C}{C_0} = e^{-(T / T_r)} 
\]

5)

\[
\ln \frac{C}{C_0} = -(T / T_r) 
\]

6)

In complete mixed reactors, graphing \( \ln(C / C_0) \) versus \( T / T_r \) yields a line and in ideal conditions all data points are exactly located on the line. In this condition, \( R^2 \) of linear regression of \( \ln(C / C_0) \) versus \( T / T_r \) is equal to 1. Any deviation of hydraulic regime from completely mixed condition affects and decreases the quantity of this parameter to less than 1. Thus fitness of data with complete mixed model and determination of \( R^2 \) of linear regression in experimental data can be useful to determine whether a complete mixed hydraulic regime is achievable in the reactor. Relatively less data points are required, which is one of the advantageous features of this method.

**MATERIALS AND METHODS**

Hydraulic characteristics in an ASFFR were studied in the preliminary phase of comprehensive research on the behaviour of this system in removing various organic loading rates. Fig. 1 illustrates the pilot plant which was used in this research.

**Fig. 1**- Scheme of Aerated Submerged Fixed-Film Reactor in the Study

Studies were conducted in a 1.8 m tall, 25 cm diameter Plexy-Glass Cylinder, packed with 11000 tabular PVC media. The length and diameter of each PVC medium were 1.2 cm and 0.6 cm, respectively. The useful volume of the reactor was 66.18 L with packed ratio of 15.68%. Upflow current was provided using an adjustable dosing pump with a range of 4-35 L/hr. The air supply of reactor was provided using a compressor with tank capacity of 150 L and 6 atm
The concentration of Rhodamine-B was determined according to spectrophotometry at 555 nm. A 50 mg/L reference solution was prepared and then diluted to concentrations of 20-50-80-100-200-400-600-800-1000 ug/L. Based on the absorbance of each prepared standard at 555 nm and linear regression of data the following equation was set.

\[
  \text{Conc. (\mu g/lit) = \frac{(\text{Absorbance} - 0.001378)}{(2.23923 \times 10^{-4})}} 
\]

Independent variables in this phase were water flows and air supply. Water flow was changed from 4.616 to 14.153, 23.356 and 30.763 L/hr respectively and each flow was studied without air supply to simulate plug-flow condition and also with air supply of 10, 20 and 30 L/min. Hence, 16 different state have been evaluated.

In each run, after pulse input of tracer and 1 minute rapid mixing of the content of reactor, initial concentration was determined. Then samples were collected from the effluent of the system in time periods of 20-60 min (based on flow rate) and concentration of Rhodamin-B determined. Sampling and determination of tracer concentration were continued up to the the minimum detectable concentration.

For calculating the Dispersion Number, a program was developed in FOXPRO. This program can compute Dispersion Number and parameters which are used to graph time distribution curves. Required data of the program are: tracer concentrations (C), related elapsed time (ti), initial concentration of tracer in reactor (0), and hydraulic detention time (Tr). The following steps presented here describes how to use the program.

Step 1: A file with following fields structure should be made in FOXPRO

Field   Field Name   Type   Width   Dec

1 T       Numeric     12      4
2 C       Numeric     12      2
3 CAL_T_TR Numeric 12 6
4 CAL_C_C0 Numeric 12 6

5 TC Numeric 12 2

6 T2C Numeric 12 2

If a file with this structure exists previously, its structure can be copied to the desired file as follow:

COPY STRU TO *File name*

Step 2: tracer concentrations (ci) and related elapsed time (ti) are entered to the file.

Step 3: Execution of the routine DISPERSION as below:

DO DISPERSION

At this step, the following statement appears. In response, the name of data file should be addressed.

ENTER THE DATA FILE :

Then two question statements appears as follows which should be answered correctly.

INITIAL TRACER CONCENTRATION:

THEORETICAL DETENTION TIME:

After these steps the computation performs and output will appears. For example output file of data for water-flow of 30.763 L/hr and air supply of 10 L/min is illustrated in Table 2.

**Table 2- Example of Output File of Designed Program**
(for water-flow of 30.763 L/hr and air supply of 10 L/min

```
" ORDER OF VARIABLES FROM LEFT TO RIGHT:"

"TIME,CONCENTRATION,CALCULATED T/TR,CALCULATED C/C0,THEORETICAL C/C0,T/TBAR,TC,T2C"

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Concentration</th>
<th>C/C0</th>
<th>T/TR</th>
<th>C/C0</th>
<th>T/TBAR</th>
<th>TC</th>
<th>T2C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0000</td>
<td>654.79</td>
<td>0.154955</td>
<td>0.7594176</td>
<td>0.856454</td>
<td>0.269</td>
<td>13095.80</td>
<td>261916.00</td>
</tr>
<tr>
<td>40.0000</td>
<td>529.74</td>
<td>0.309909</td>
<td>0.642506</td>
<td>0.733513</td>
<td>0.537</td>
<td>21189.60</td>
<td>847584.00</td>
</tr>
<tr>
<td>60.0000</td>
<td>435.96</td>
<td>0.464864</td>
<td>0.528763</td>
<td>0.628221</td>
<td>0.806</td>
<td>26157.60</td>
<td>1569456.00</td>
</tr>
<tr>
<td>80.0000</td>
<td>333.25</td>
<td>0.619819</td>
<td>0.404189</td>
<td>0.538042</td>
<td>1.075</td>
<td>26660.00</td>
<td>2132800.00</td>
</tr>
<tr>
<td>100.0000</td>
<td>261.80</td>
<td>0.774773</td>
<td>0.317530</td>
<td>0.460808</td>
<td>1.344</td>
<td>26180.00</td>
<td>2618000.00</td>
</tr>
<tr>
<td>120.0000</td>
<td>221.60</td>
<td>0.929728</td>
<td>0.268772</td>
<td>0.394661</td>
<td>1.612</td>
<td>26592.00</td>
<td>3191040.00</td>
</tr>
<tr>
<td>140.0000</td>
<td>172.48</td>
<td>1.084683</td>
<td>0.209196</td>
<td>0.338009</td>
<td>1.881</td>
<td>24147.20</td>
<td>3380608.00</td>
</tr>
<tr>
<td>160.0000</td>
<td>136.75</td>
<td>1.239637</td>
<td>0.165860</td>
<td>0.289489</td>
<td>2.150</td>
<td>21880.00</td>
<td>3500800.00</td>
</tr>
<tr>
<td>180.0000</td>
<td>92.09</td>
<td>1.394592</td>
<td>0.111693</td>
<td>0.247934</td>
<td>2.419</td>
<td>16576.20</td>
<td>2983716.00</td>
</tr>
<tr>
<td>200.0000</td>
<td>69.77</td>
<td>1.549547</td>
<td>0.084622</td>
<td>0.212344</td>
<td>2.687</td>
<td>13954.00</td>
<td>2790800.00</td>
</tr>
</tbody>
</table>

"Initial Concentration: 824.49"

"Theoretical Detention Time : 129.07"
After performing the tracer study, biological startup of pilot was performed using glucose as carbon source. Nitrogen and phosphorous were added proportional to influent BOD using ammonium chloride and ammonium phosphate. Influent BOD:N:P was adjusted according to ratio of 100:5:1. The reactor was inoculated with microbial mass consisting of the secondary sludge of a sanitary wastewater treatment plant. After reaching steady state condition, the carbonaceous substrate was replaced with ethylene glycol. In this stage 4 hydraulic loading levels were studied. Influent COD was adjusted to 500 mg/L and was not changed during the study. In this way organic loading was increased by increasing of hydraulic loading of wastewater to the reactor. Pilot plant effluent was monitored during each run and after reaching steady state condition samples were collected from each sampling ports simultaneously and concentration of soluble COD, alkalinity, phosphorous, and nitrate determined to show the effect of biological growth on the uniformity of the system.

RESULTS AND DISCUSSION

According to the described methodology, dispersion numbers were determined for 16 different states in the tracer study. Data in Table 3 shows that, apart from the state when no air was supplied to the system, in all other conditions dispersion numbers were more than 0.2. This means that well mixed condition were maintained. Variation of water
flows and air supplies in the experienced range in this study did not show any significant change in dispersion number. When there was no air supply to the reactor, dispersion number variation was significant and reactor showed Plug-Flow behaviour.

Table 3- Dispersion Number in Different Condition During Tracer Test.

<table>
<thead>
<tr>
<th>Influent Wastewater Flow (L/hr)</th>
<th>Air Supply (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>4.616</td>
<td>0.081</td>
</tr>
<tr>
<td>14.153</td>
<td>0.107</td>
</tr>
<tr>
<td>23.153</td>
<td>0.092</td>
</tr>
<tr>
<td>30.763</td>
<td>0.111</td>
</tr>
</tbody>
</table>

On the other hand as shown in Table 4, fit of data with the complete mixed model indicated that in all test condition, except when no air supply exists, more than 90 percent of data fit with the completely mixed model was obtained.

Table 4- results of Tracer test Data Fitness with Complete Mixed Model according to $R^2$

<table>
<thead>
<tr>
<th>Air Supply (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
</tbody>
</table>
Figs. 2-5 illustrate the variation of $(\ln C/C_0)$ versus $(T/Tr)$ in each of the 16 test condition. Even when there was no air supply in the system, for lower water flows (longer detention times), dispersion occurred in reactor due to diffusion. In other cases the role of air supply in mixing was less relative to cases with shorter detention time.

**Fig.2** - $\ln(C/C_0)$ Vs. $T/Tr$ for Wastewater Flow of 4.416 L/hr

**Fig.3** - $\ln(C/C_0)$ Vs. $T/Tr$ for Wastewater Flow of 14.153 L/hr

**Fig.4** - $\ln(C/C_0)$ Vs. $T/Tr$ for Wastewater Flow of 23.153 L/hr

**Fig.5** - $\ln(C/C_0)$ Vs. $T/Tr$ for Wastewater Flow of 30.763 L/hr

As mentioned, pilot plant effluent was monitored during each experiment and samples collected from each sampling port simultaneously in steady state conditions to show the effect of biological growth on mixing. Concentrations of soluble COD, alkalinity, phosphorous, and nitrate, determined to show the effect of biological growth on the uniformity of the system, are shown in Table 5 for different loadings. As the variation of parameters at each sampling port is not significant for different loadings, it is concluded that in the range of loadings used in this study there was not significant variation of concentration of the measured parameters along the reactor. Therefore biological growth of film on supporting media did not change the mixing pattern significantly.

**Table 5- Concentration of COD, NO₃⁻, ALK, P at different Ports after reaching Steady State Condition**
<table>
<thead>
<tr>
<th>Parameters:</th>
<th>SCOD (mg/L)</th>
<th>NO3 (mg/L)</th>
<th>ALK (mg/L) As CaCO₃</th>
<th>Soluble P (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot Runs*</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Sampling Port 1 (Top)</td>
<td>34</td>
<td>36</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td>Sampling Port 2</td>
<td>34</td>
<td>36</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td>Sampling Port 3</td>
<td>34</td>
<td>36</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td>Sampling Port 4</td>
<td>36</td>
<td>36</td>
<td>41</td>
<td>48</td>
</tr>
<tr>
<td>Sampling Port 5</td>
<td>34</td>
<td>36</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Sampling Port 6 (Bottom)</td>
<td>62</td>
<td>56</td>
<td>68</td>
<td>60</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>11.3</td>
<td>8.16</td>
<td>12.53</td>
<td>7.01</td>
</tr>
</tbody>
</table>

*Test Conditions:
1- 4.616 L/hr (detention Time=11 hrs)

2- 14.153 L/hr (detention Time=8 hrs)

3- 23.153 L/hr (detention Time=6 hrs)

4- 30.763 L/hr (detention Time=4 hrs)

ND= Not detectable

CONCLUSIONS

In this research flow characteristics of an Aerated Submerged Fixed-Film Reactor before start-up and also after reaching steady state condition with different detention time was studied. Tracer tests were performed and data analyzed to determine dispersion number in each condition. Samples from different ports along the reactor were analyzed to characterize the effect of biological growth on mixing. The results showed that in the experienced range of flow and air supply, the well-mixed condition is available. Furthermore analyzed samples from different ports showed that in different applied hydraulic loadings, there was no significant lack of uniformity of concentration in the system. So biological growth did not pose any critical lack of uniformity of concentration during the test.

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FIG. 1 - Scheme of Aerated Submerged Fixed-Film Reactor in the Study

Air Entrance

Sampling Ports

1

2

3

4

5

6

Settling unit
* Upflow

Aerated Submerged Fixed-Film Reactor
* Upflow

Inlet
FIG. 2: Ln(C/C0) vs. T/Tr for Wastewater Flow of 4.416 Lit/hr
FIG. 3.\[\text{Ln}(C/C_0)\] vs. T/Tr for Wastewater Flow of 14.153 Lit/hr
Figure 4: \( \ln\left(\frac{C}{C_0}\right) \) vs. \( T/Tr \) for Wastewater Flow of 23.153 Lit/hr.
FIG. 5- Ln(C/Co) Vs. T/Tr for Wastewater Flow of 30.763 Lit/hr