Hydrodynamics and mixing characteristics of packed bed biofilm reactor with varying voidage

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Abstract. In the present study, hydrodynamics and mixing characteristics of packed bed biofilm reactor are compared by varying voidage using MBBR media and conventional packings. The mixing characteristics are studied using conductivity method. RTD at the entrance and exit of the column is studied and compared for all the packings. The flow approached plug flow with an increase in velocity (3.02 - 5.2 cm/s) and a decrease in voidage of packing (0.92 - MBBR, 0.833 – Raschig rings, 0.45 – Plastic balls).

Introduction
The Biofilm Packed Bed Reactor (BPBR) is one of the commonly used reactor in the biological treatment of waste water [1]. BPBR has several industrial applications like waste water treatment plant, Pharmaceuticals, Petroleum industry and in the environmental sciences [2]. The efficiency of the biofilm depend on the conditions in which the biofilm is developed and so the hydrodynamics and mixing characteristics of the process. The operating conditions of conventional packed bed reactor and biofilm packed bed reactor are different as the range of operating conditions are further restricted in BPBR [3]. The operating conditions are limited to avoid excess shear over the operating liquid, to provide required contact and residence time. For better design and operation of any equipment, hydrodynamics and mixing characteristics are important. Among the suitable operating conditions identified from the hydrodynamic characteristics, identifying and accounting for non idealities in continuous flow reactors are indispensable as the flow pattern and the non idealities will affect the mass transfer rate of the reactor [4]. The non idealities in the packed bed are not only depend on the experimental conditions, but also depend on the nature of packing and its size in packed bed reactor. There are many studies reported in the literature related to RTD in the conventional packed bed reactor, but not many on BPBR Hence, in the present work, it is proposed to study the effect of voidage with various packings on the mixing characteristics of biofilm packed bed reactor.

Experimental Methods
The hydrodynamic and mixing characteristics studies are carried out in BPBR (Shown in Figure 1a & b) made of an Acrylic cylindrical tube of length 100 cm and diameter of 7.5 cm. The PVC strainers are used as the packing support and a thin mesh is used as the distributor between the packings. In the test section, ports are provided at the top and at the bottom of the column to measure pressure drop by connecting it to a U-tube manometer. Two stainless steel rods of diameter 8 mm are inserted in to the each sides of the test section and used to measure conductivity across the diameter of the pipe. This conductivity measurement provision is provided at the beginning and before ending of the packings. The conductivity across the column is measured using conductivity meter (SA-303) and the conductivity signal is recorded in the system at the rate of 10 samples per second. For the given liquid
velocity, after the system is attained the steady state, pressure drop in the manometer is recorded. And then, 5 ml of 5 N NaCl solution is injected by imperfect pulse method at the top of distributor and the conductivity signal variations are recorded. The same procedure is repeated for various liquid flow rates and packings including spherical balls, Raschig Rings and Moving Bed Biofilm Reactor (MBBR) media. The properties of the packings and liquid are given in the Table 1.

Results and discussion
Hydrodynamics
The effect of flow rate on the pressure drop across the packed bed with various packings is shown in Figure 2. The pressure drop linearly increase with an increase in the liquid velocity irrespective of the packing and its size due to the energy loss by friction between packing and walls with liquid. Among the packings studied in the work, pressure drop with spheres are higher than the MBBR media and Raschig rings. The pressure drop is higher with low voidage packing (Spheres), as the interstitial velocity is high due to the availability of less cross sectional area. The pressure drop with MBBR media is very less which indicates the energy requirement of biofilm packed bed with MBBR Media is low.

Residence time distribution
The salt concentration measured at the inlet and outlet of the column is shown in Figure 3 for MBBR. Due to the axial dispersion due to the liquid flow in the reactor, there is a broader distribution in the time at which the salt tracer concentration is measured. The exit age distribution is calculated by the procedure mentioned in Levenspiel (1972) [5] where,

$$E(t) = \frac{C_{pulse}}{\int C dt}$$

Where, C is the Concentration (mg/l), E is the Exit Age Concentration, dt is the difference in time and shown in Figure 4 for MBBR. The exit age distribution is broader than the entry age distribution which indicates the dispersion in the flow and its deviation from the plug flow can be understood. The distribution is normalised by using mean residence time ($\bar{t}$) as $E(\theta)$ as follows. The $E_0$ is a dimensionless quantity and it is independent of flow rate. This term is used where dispersion in the reactor dominates. The formula given below is used to find ($\bar{t}$)

$$\bar{t} = \frac{\int tC dt}{\int C dt}$$

The $E(\theta)$ is calculated by

$$E(\theta) = \frac{C_{pulse}}{M} = \bar{t} E(t)$$

$C_{pulse}$ is the concentration and the $M = V/\nu$ is the velocity. The effect of flow rate and various packings with different voidage on $E(\theta)$ is shown in Figure 5 and 6 respectively. As the interstitial velocity increases with an increase in the flow rate, the dispersion of molecules decreases. Hence, the $E(\theta)$ curve becomes narrower, which indicates the flow is approaching plug flow whereas at low liquid velocity, the dispersion is maximum and so the curve is broader. In case of MBBR, it can be seen from the broader $E(\theta)$ curve, that the dispersion is relatively high. And also, the $E(\theta)$ curve becomes narrower with packing in the order MBBR < Raschig rings < Spheres, as the voidage decreases. The available cross sectional area decreases with decreasing voidage that results in narrower $E(\theta)$ curve indicating the flow approaches plug flow.

Conclusion
Hydrodynamic and mixing characteristics of biofilm packed bed reactor are studied. Total pressure drop across the bed linearly increases with an increase in liquid velocity. The pressure drop across the bed decreases with an increase in voidage of the bed. With an increase in liquid flowrate, the spread of RTD decreased and the spread increased with an increase in voidage. Even though, RTD spread is more with MBBR, the shear exerted over the liquid is relatively minimal and the fraction of liquid available to treat in the column is relatively high.
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| S. No. | Packings            | Diameter (cm) | Density (g/cc) | Porosity |
|-------|---------------------|---------------|----------------|----------|
| 1.    | Plastic spheres     | 0.5           | 0.423          | 0.45     |
| 2.    | Raschig Rings       | 1             | 0.31           | 0.833    |
| 3.    | MBBR Media          | 2.5           | 0.130          | 0.93     |
Fig. 1a Schematic of the experimental setup

Plastic Balls

Raschig rings
Fig. 1b BPBR and packings
Fig. 2 Effect of liquid velocity on various packings

Fig. 3 Concentration distribution

Fig. 4 Residence time distribution
Fig. 5 Effect of flow rate on $E(\theta)$

Fig. 6 Effect of packing material on $E(\theta)$