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COMPARTMENT-WISE VARIATION OF HYDRODYNAMIC CHARACTERISTICS OF THE MODIFIED ANAEROBIC BAFFLED REACTOR

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ABSTRACT

The anaerobic baffled reactor (ABR) possesses many advantages such as high removal efficiency, outstanding working stability, and lower operating cost. These include better residence to hydraulic and organic shock loadings, longer biomass retention times, lower sludge yields, and the ability to partially separate between the various phases of anaerobic catabolism. In this study, a reactor having effective volume 45.0 L was designed with seven compartments. The compartments had major two parts: first five chambers called anaerobic baffled reactor (ABR) and last two chambers called fluidized bed reactor (FBR). The external dimensions were 90, 19, and 29cm for length, width, and depth, respectively. The residence time distribution analyses was carried out by using tap water on clean reactor through tracer Pulse Input Experiment technique, to investigate compartment-wise mean residence time, mixing patterns, dead spaces and hydraulic efficiency in this novel type of reactor. The results show that the hydrodynamic characteristics of the anaerobic baffle reactor directly depends on the number of compartments. The mean residence time increases with the increase in the ABR compartments. The dead spaces in 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber of the ABR were 54.01, 36.56, 21.75, 11.42, 9.57, 6.27 and 0%, respectively indicates that the dead space decreases with the increase in the ABR compartments. In addition, the increase in ABR compartments also resulted in the decrease in back-mixing and $1/Pe_z$ values (from 0.53 to 0.07), which made the fluid in the reactor approach to the plug flow state.

Keywords: *Anaerobic baffled reactor, mean residence time, dead space, back-mixing, hydraulic efficiency*

1. INTRODUCTION

Sanitation is the hygienic means of promoting public health through prevention of human contact with the hazards of wastes. Without proper sanitation, people cannot attain to avoid proper preventable disease. It is the utterly important role of proper sanitation in achieving and maintaining good public health. The need for proper sanitation was made explicit in the United Nations Millennium Development Goals. Goal number 7 urges for the reduction by half of the population living without proper sanitation. Despite significant efforts, progress on sanitation targets is very slow and still lacking behind. Acknowledging the impact of sanitation on public health, poverty reduction, economic and social development and the environment. Important in this is to not only connect people to sanitation solutions, but to make this connection last in an environmentally sustainable way (Henze, 2008).

Besides improved sanitation, hygiene and safe water save millions of lives, accelerate economic growth, enhance people’s dignity, and create a better future for all. Many countries are challenged in providing adequate sanitation for their entire populations, leaving people at risk for water, sanitation, and hygiene (WASH) related diseases. Throughout the world of 7.3 billion people, 2.4 billion lack access to adequate sanitation that it is more than 35% of the world's population and 1 billion have no choice but to defecate in the open, without access to even basic toilets or hand washing facilities (EMI: Water Sanitation & Hygiene, 2016). One out of every three in rural areas are defecated in the open and their neighbors are affected to fecal bacteria that lead to diarrhea and other diseases. Roughly half a million children die every year from diarrhea caused by unsafe water and poor sanitation. Half of the hospital beds in the developing countries are filled with people suffering from diseases caused by poor water, sanitation, and hygiene (The Sanitation Crisis, 2016). Most people without adequate sanitation live in Sub-Saharan Africa and South Asia. Without immediate acceleration in progress of sanitation, the world will not achieve the United Nations' Sustainable Development Goals (SDGs) by 2030.

Bangladesh is one of the most densely populated countries in the world, with more than 1222 per square kilometre. As Bangladesh experiences one of the fastest urbanization rates in Asia, most of the 7 million people living in urban slums – the population of which is rapidly increasing but they have no access to improved sanitation. Overall 39 percent people lack of improved sanitation facilities in rural areas, overcrowded conditions, and a lack of healthy ways of disposing waste in urban centers (Bangladesh Water Crisis, 2014).

One of the main concern of sanitation is wastewater treatment. Wastewater can be treated both aerobically and anaerobically. Anaerobic treatment of wastewater is most popularly used due to: (a) zero consumption of oxygen which cuts down the cost and energy requirements; (b) sludge production rate is very low which reduces the cost of sludge handling, stabilization, and final disposal; (c) production of biogas which can be used as a fuel; and (d) high COD removal efficiency (Xu et al., 2014). The advent of the high rate anaerobic treatment methods in which solids/sludge retention time (SRT) is long period occurs at low hydraulic retention time (HRT). Good contact between the biomass and substrate at low reactor volume is ensured by immobilizing the biomass as a result of granulation of biosolids.

Anaerobic treatment of wastewater has existed as a practical technology for over 100 years. It gradually evolved from a simple uncontrolled septic tank system. Septic tank usually fails to sanitize and contribute to groundwater pollution. In addition, septic systems often discharge into the environment with little or no sanitization or nutrient removal due to faulty design. Faulty design means poor hydraulic characteristics and mixing pattern. Moreover, the hydraulic flow regime in such a system is in the horizontal direction. This hydraulic phenomenon increases the possibility of short circuiting and dead spaces which reduce the actual or mean hydraulic retention time (HRT). As a consequence, the reduced HRT with the horizontal flow mode significantly diminishes the contact between the incoming substrate and the active biomass accumulated at the bottom of the septic tank, resulting in reduction of the treatment efficiency (Sharma & Kazmi, 2015). Now a days, completely controlled reactors used for treating wastewater. In anaerobic systems, the key microbial populations have a lower reproductive growth rate than aerobic reactors. But a longer sludge retention time (SRT) is to be provided in order to allow a stable equilibrium to be achieved between the diverse microbial community members in the anaerobic sludge (Xu et al., 2014). The loading rates permissible in an anaerobic waste treatment process depend on the concentration of active biomass within the digester. The major point of interest in the practical application of anaerobic process is the maintenance of a high solids retention time (SRT 20-100day), while keeping the hydraulic retention time (HRT) to a minimum (1.3~20 h) (Langenhoff et al, 2000). The solids retention time (SRT) is to be maintained well in excess of the hydraulic retention time (HRT). This results in higher biomass densities within the system. To accomplish the higher treatment efficiency and reliability associated with a long SRT, a number of novel anaerobic reactor configurations have been developed. Among of them the Anaerobic Baffled Reactor (ABR) is a novel type of reactor first described by Bachmann *et al* (1983), which allows high rates of hydraulic throughput with very little loss of biomass from the reactor, and a high reaction rate per unit volume (Krishna et al., 2009). The ABR achieves this by means of a design which is both simple and cheap to construct, since there are no moving parts or mechanical mixing devices. High residence times of bacterial cells within the reactor have been found, together with good mixing, providing a high rate of contact between the cells and their substrate (Grobicki & Stuckey, 1992).

The performance of the anaerobic baffled reactor (ABR) mainly depends on hydrodynamic characteristics of the reactor. The flow patterns of the reactor greatly influence back-mixing, dead spaces, and volumetric efficiency of the reactor which consequently affects treatment efficiency, working stability, reaction time, and equipment investment (Li et al., 2016). A good flow pattern promotes the substrate transferring to microorganisms, maintains uniformity of environmental factors thereby assuring the effective use of the reactor volume. Therefore, it is imperative to understand the performance of the flow patterns of the ABR and the correlation between the flow pattern and back-mixing, dead spaces and volumetric efficiency (Xu et al., 2014). So the flow patterns and optimization of compartments for anaerobic baffled reactor is an important issue.

So tracer experiments are often conducted to estimate the residence time distribution (RTD) and the time distribution for particles entering and leaving the system. Residence time distribution (RTD) analyses are carried out to investigate the hydraulic characteristics of the ABR (Sarathai et al., 2010). Therefore, RTD curves obtained from tracer tests. The curves can be used to analyse the compartment-wise residence time, mixing pattern, dead spaces, and hydraulic efficiency of the modified reactor.

2. METHODOLOGY

2.1 Experimental Set-up

A bench scale reactor used in this experimental study was constructed with clear acrylic plastic. The reactor has seven chambers. The external dimensions were 90, 19, and 29 cm for length, width, and depth, respectively. The reactors were rectangular, containing standing baffle, hanging baffle, and inclined baffle shown in figure-1. The standing baffles divided each reactor into seven identical compartments. The length of the compartments was varying according to its position. The first chamber length was 22cm, second to fifth chamber length 11cm, and last two chamber length 12cm. The hanging baffles which were designed in the compartments of the ABR divided each compartment into a down-flow section and an up-flow section. The up-flow/down-flow ratio was 4:1. The lower portion of the inclined baffles was bent at 45° to route the flow to the centre of the up-flow chamber, thus achieving better contact and greater mixing of feed and bio-solids. The total working volume of the reactor was 45L. The treatment of wastewater in a baffled reactor were the inability to produce a floating sludge layer which would enhance solids retention and the high velocities associated with the baffles caused significant washout of solid material. So that the 1st chamber of the ABR was doubled in size than other chambers. The flow rate was adjusted by dosing pump.

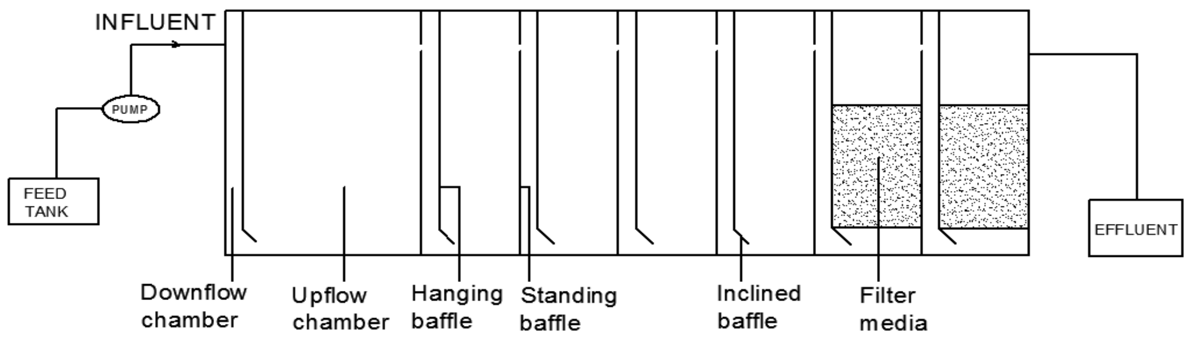

Figure 1. The schematic diagram of experimental setup.

2.2 Anaerobic Filter

The last two chambers of the baffle reactor were used as fluidized bed reactor. The anaerobic filter chambers of each unit were packed with Shredder plastic bottle cork shown in figure-2. The bottle cork used as a filter media is low specific gravity and floating in water so that its porosity is high. Also specific surface area is high. Also the bottle cork are locally available. The amount of bottle cork used in each chamber was 400gm. The figure of shredded plastic bottle cork given below:

Figure **Error! No text of specified style in document.**. Filter media used in the study.

2.3 Pump Calibration

A dosing pump was used to feed the reactor shown in figure-3. A dosing pump is a small positive displacement pump. It was designed to pump a very precise flow rate. Dosing pumps was used in a variety of applications from agriculture, industry, manufacturing to medicine. The pump used in this study was operated 0~360 stocks and maximum flow 334 ml/min at 360 stocks. For 3 hours residence time distribution (RTD) analysis, the baffle reactor was feed 15 L/hrs. In order to achieve the required flow the pump was calibrated. From calibration curve, the required stock was obtained.

Figure 3. Dosing pump

2.4 Experimental Design

The experimental setup of the tracer study shown figure-4. The hydraulic characteristics of the system were determined by residence time distribution (RTD) curves. The RTD curves, the time distribution for particles entering and leaving the system was obtained from tracer studies and further analysed for mixing pattern. Tracer studies were performed by using pulse input technique. Sodium chloride (NaCl) was selected as the tracer due to its various favourable features. In the study, the ABR was feed only tap water in the influent and the tracer was pulsively injected (t=0) at the inlet of the ABR. The tracer was quickly injected into the reactor in less than 5 sec. Samples were collected at the tracer collection point for at least twice during the designed hydraulic retention time (HRT). The EC of the collected sample was measured by multimeter and using EC calibration curve the concentration of NaCl was obtained. It was expressed as C(t). Then normalized time vs. tracer concentration of each chamber was plotted. The resulting response curve, referred as the C-diagram, provided an accurate representation of the hydraulic regime of the system.

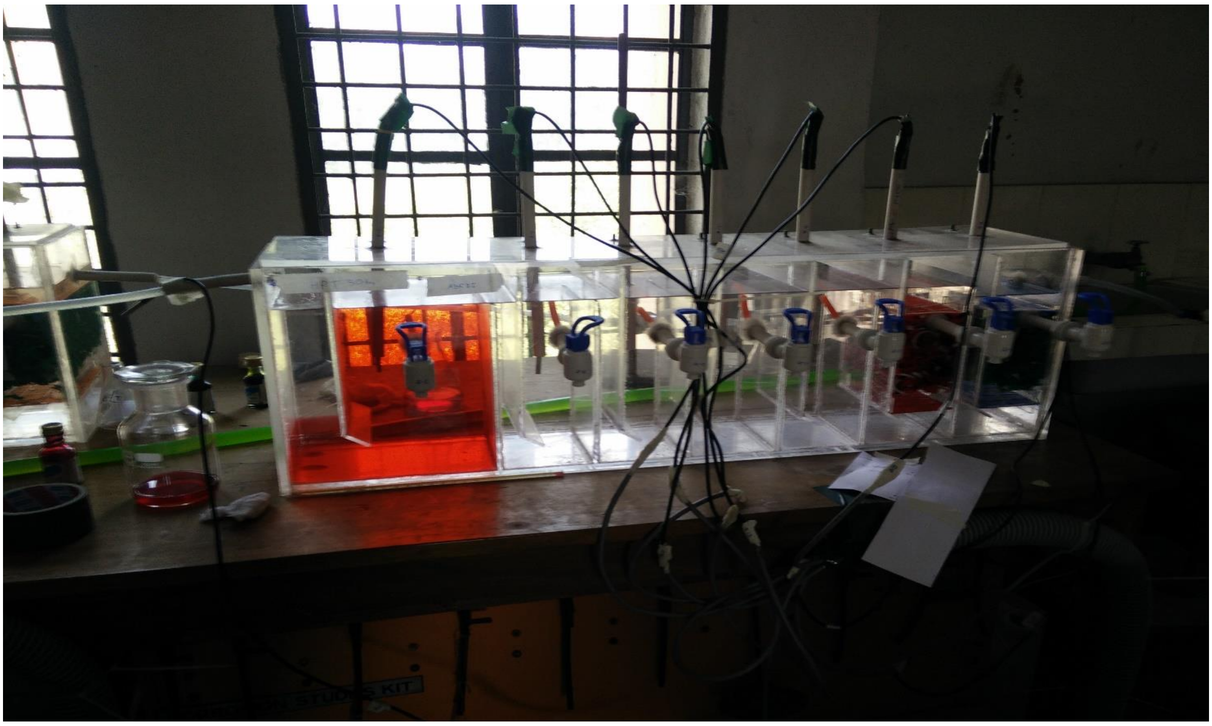

Figure 4. Experimental setup during tracer test.

2.5 Theoretical analysises

To analyze the behavior of the reactor the normalized RTD functions $E(t)$, mean residence time (τ) and distribution variance (σ^2) were calculated by the following equations:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \qquad (1)$$

$$\tau = \frac{\int_0^\infty tE(t)dt}{\int_0^\infty E(t)dt} \qquad (2)$$

Where $\int_0^\infty E(t)dt = 1$

$$\sigma^2 = \int_0^\infty t^2 E(t)\,dt - \tau^2 \qquad (3)$$

The dead spaces present in a reactor reduce the active volume of system. The percentage of the dead space can be calculated by the following equation:

$$V_d = \left(1 - \frac{\tau}{HRT}\right) \times 100\% \qquad (4)$$

σ_θ^2 is the dimensionless variance of the RTD and $\sigma_\theta^2 = \sigma^2/\tau^2$

$$\sigma_\theta^2 = 2\left(\frac{D}{uL}\right) - 2\left(\frac{D}{uL}\right)^2\left(1 - e^{-uL/D}\right) \qquad (5)$$

Where, D/uL is the dispersion number (dimensionless), which characterizes the degree of back-mixing in the direction of flow. If D/uL = 0, the reactor approximated to the ideal plug-flow reactor (PFR, D/uL = 0). If D/uL =∞, the reactor approximated to the ideal continuous-flow stirred-tank reactor (CSTR, D/uL = 1).
The tank-in-series model could be calculated by

$$N = \frac{1}{\sigma_\theta^2} \qquad (6)$$

If $N = 1$, then the reactor approximated to the CSTR, and if $N = \propto$, then the reactor approximated to the PFR.
The hydraulic efficiency (λ) expressed in Eq. (7) reflects two basic features: the effective volume and near-plug flow condition. Values of both terms range from 0 to 1, providing equal weighting for effective volume and pollutant hydraulic residence time distribution. The hydraulic efficiency can be categorized into three groups:

(i) Good hydraulic efficiency with $\lambda > 0.75$;
(ii) Satisfactory hydraulic efficiency with $0.5 < \lambda \leq 0.75$; and
(iii) Poor hydraulic efficiency where $\lambda \leq 0.5$

$$\lambda = e\left(1 - \frac{1}{N}\right) \qquad (7)$$

Where, e is the effective volume, calculated as one minus dead space and *N* is the number of on continuous stirred tanks in series.

3. RESULTS AND DISCUSSIONS

3.1 RTD of ABR

The RTD curves obtained by plotting normalized time vs. concentration (mg/L). Fig. 5. shows the RTD of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR, respectively. As shown in the figure, the reactor residence time curve firstly rises and then drops, forming one single peak. The calculated peak concentrations of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR were 1021, 684, 593, 548, 506, 463, 447, and 417 mg/L, respectively. Further analysis of the RTD of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR showed that, with the increase in the ABR chambers, the peak value of the RTD curves decreased as well, while the distribution width of the RTD curves turned wider on the time axis.

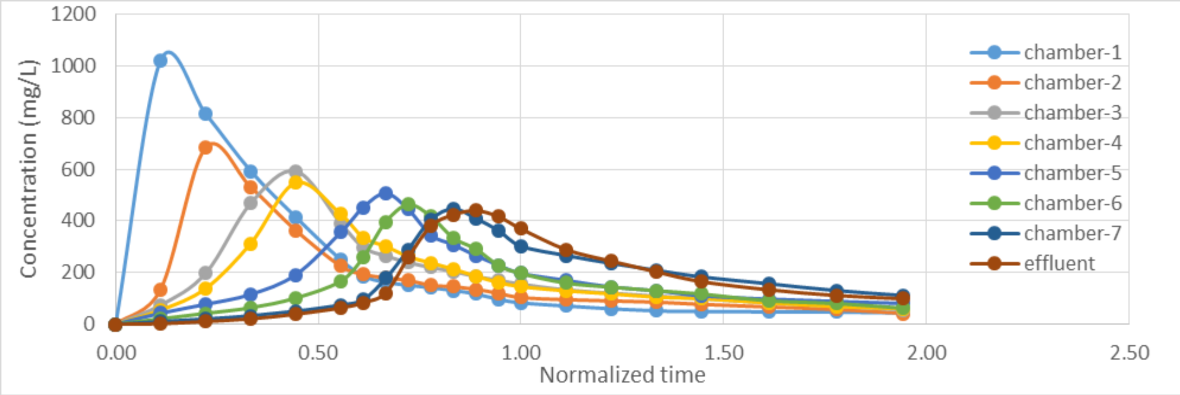

Figure 5. RTD results of various chambers.

3.2 Mean Residence Time

The mean residence time of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR were 82.8, 114.2, 140.9, 159.4, 162.8, 168.7, 181.7, and 184.1 min, respectively shown in fi. The analysis of the RTD of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber showed that, with the increase in the ABR chambers, the mean residence time also increase. For 3-hour HRT study, the mean residence time was obtained at chamber-6. That's mean the atoms leave the reactor to spend enough time.

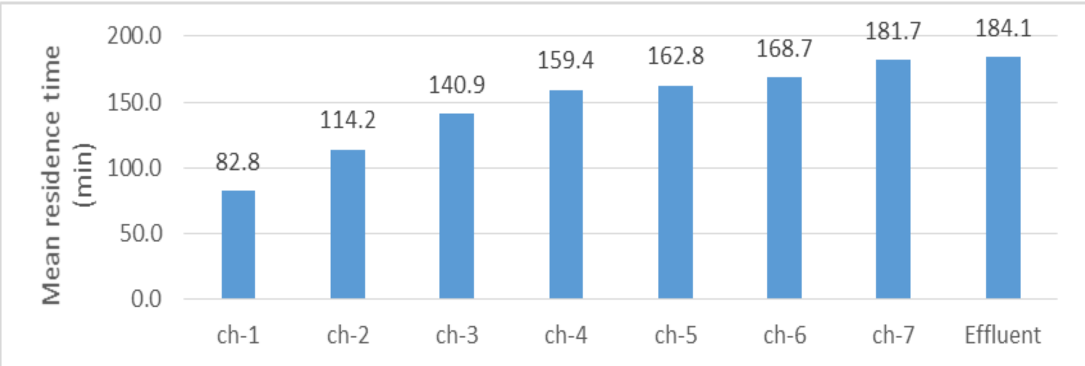

Figure 6. Mean residence time of various chambers.

3.3 Back-mixing

Peclet Number of quasi (Pez) is the ratio of the rate of the convective flow to the rate of the axial diffusion, which is often used to indicate the degree of back-mixing. When Pez tends 0 (namely, $1/Pez$ tends to ∞), the advection is much greater than the diffusion; that is to say, the fluid is completely in the form of mixed flow. On the contrary, when Pez tends to ∞, (Namely, $1/Pez$ tends to 0), the influence of the diffusion upon the convection is negligible; that is to say, the fluid is in the form of plug flow.

Analysis of the hydraulic characteristics of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR under the same operating conditions showed that, keeping the HRT value constant, the number of chambers had greater impact on the hydraulic characteristics of the ABR. The $1/Pez$ values of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR were 0.53, 0.29, 0.17, 0.14, 0.12, 0.10, 0.08, and 0.07, respectively (Fig 7). There was a great drop between the $1/Pez$ of chamber-1 and chamber-7 of the ABR; while the difference between the $1/Pez$ of chamber-7 and the effluent of the ABR was negligible.

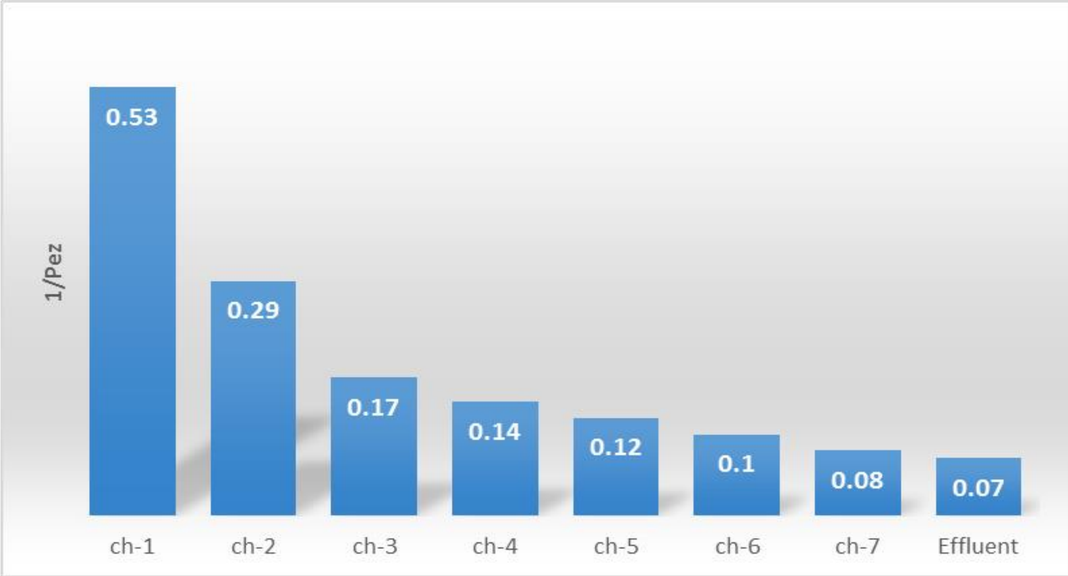

Figure 7. 1/Pez of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the ABR.

Therefore, the plug flow pattern could be obtained in the reactor by increasing the number of chambers. Tomlinson and Chambers found that when 1/Pez > 0.2, the degree of dispersion in the reactor was kept high. Likely, in this study, as the 1/Pez values of the ABR turned from 0.53 to 0.070, that the 1-, 2-chamber of the ABR were the highest. Therefore, the fluid in the 1-, 2-chamber tended to be in the form of complete mixed flow while that the 3-, 4-, 5-, 6-, and 7-chamber tended to be in the form of plug flow. As the 1/Pez value decreased, the fluid in the reactor gradually approached to the plug flow. That is to say, with the chambers increased from one to seven, the fluid in the reactor increasingly took the form of plug flow.

3.4 Dead Space

Dead space in the reactor can be generally divided into hydraulic dead space and biomass dead space. But in this study, tap water was used to analyse the hydrodynamic characteristics. So only hydraulic dead space was calculated in this experiment. As shown in Fig 8. The increase in the chambers lead to the decrease in the percentage of hydraulic dead space. The dead spaces that caused by hydraulic behaviour, in 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber of the ABR were 54.01, 36.56, 21.75, 11.42, 9.57, 6.27 and 0%, respectively (Fig 8). The dead space of chamber 6 and 7 is less than the other chambers due to the effect of fluidized bed reactor. As the dead space was zero at chamber 7. Therefore, the optimal number of chamber of the reactor shall be 6.

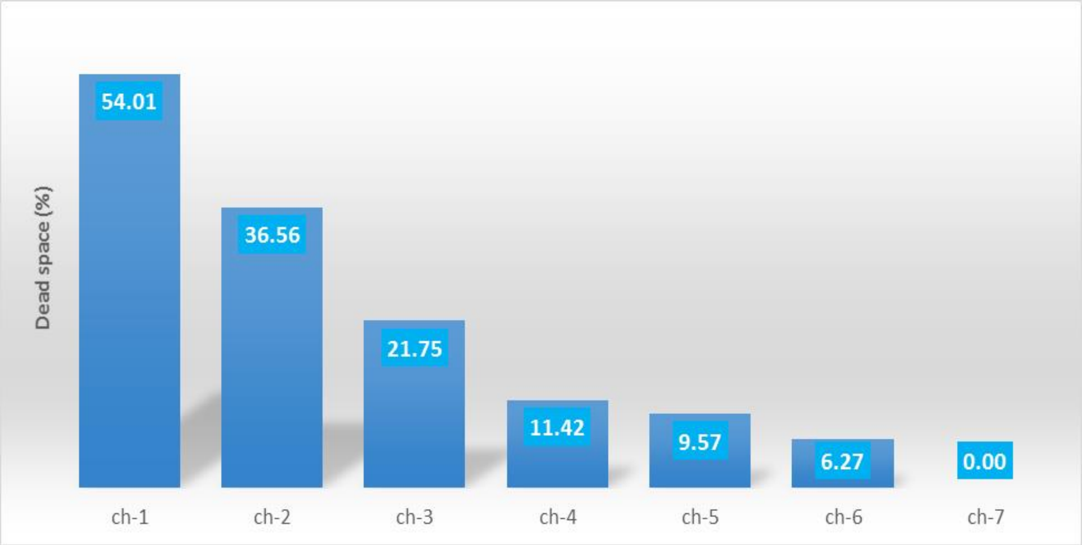

Figure 8. Percentages of dead space in 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent

The hydraulic dead space in the ABR occurs mainly at the baffle corners and the bottom free space of the inclined baffle. The existence of vortex of various degrees at the baffle corners affects diffusion of the tracer, and consequently results in slow release of the tracer; the dead space is therefore formed.

3.5 Hydraulic Efficiency

Hydraulic efficiency reflects two basic features, which are: (1) the ability to distribute the inflow evenly across the system and (2) the amount of mixing. Obviously, the satisfactory hydraulic efficiency of the ABR varies from 0.08 to 0.80 (Fig 9). However, it tended to higher when the number of chamber was increased. The hydraulic efficiency of first two chamber were 0.08 and 0.30, which is less than 0.50 that means poor hydraulic efficiency. The hydraulic efficiency of 3-, 4-, 5-, 6-chamber were 0.56, 0.75, 0.75 and 0.75, respectively. As those values is within the limit $0.5 < \lambda \leq 0.75$, so the flow in those chambers was satisfactory hydraulic efficiency. The values of 7-chamber and effluent were 0.77 and 0.80, which is greater than 0.75. So the hydraulic efficiency was very good.

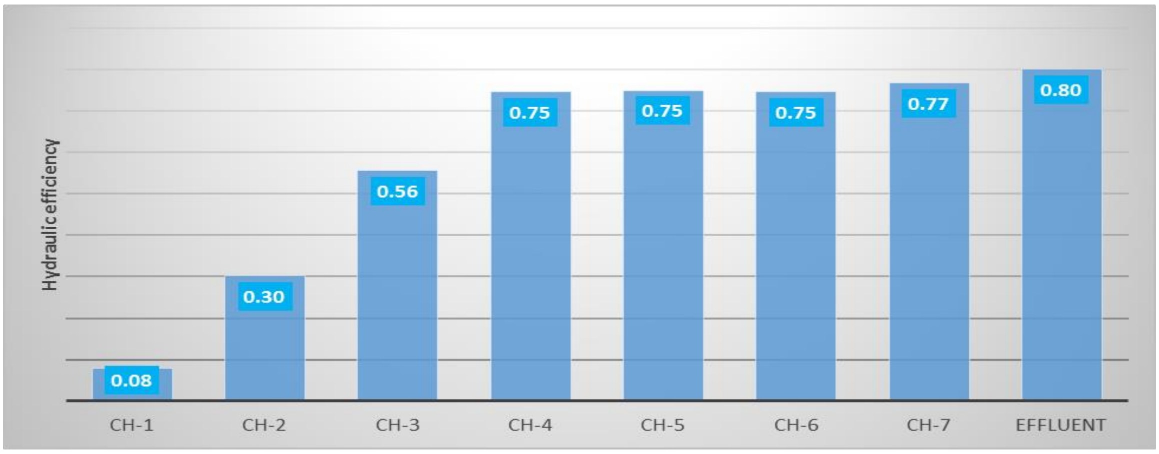

Figure 9. Hydraulic efficiency of various chambers

4. CONCLUSIONS

In conclusion, it is apparent from these studies that the ABR may be characterized as a series of well-mixed CSTRs, with low dead space. There is very little mixing between one compartment and the next, due to the baffle arrangement. Hence the ABR may be represented for the purposes of modelling as a series of ideal stirred tanks, corresponding to the number of actual compartments. With the increase in the ABR chambers, the mean residence time also increase. The greater the number of compartments, the closer the reactor will approach plug flow. Dead space may be divided into two categories, hydraulic and biological. Hydraulic dead space, which is a function of flow rate and the number of baffles, may broadly be said to increase with decreasing HRT. The dead spaces that caused by hydraulic behaviour, in 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber of the ABR are 54.01, 36.56, 21.75, 11.42, 9.57, 6.27 and 0%, respectively. The dead space in this study was very high due to low HRT, though the dead space decrease with increase the number of chamber. In the last two chambers, the dead space was reduced at a significant amount due to the effect of filter media. The hydraulic efficiency of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber of the baffle reactor are 0.08, 0.30, 0.56, 0.75, 0.75, 0.75 and 0.77, respectively. That means hydraulic efficiency is also increase with the increase of ABR compartments. Taking the operating performance and economic factors of the reactor into full consideration, the present study recommends that the series number (N) of ABR compartments shall be kept at least 6.

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