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EFFECT OF TEMPERATURE ON HYDRODYNAMIC BEHAVIOUR OF A MODIFIED ANAEROBIC BAFFLED REACTOR

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ABSTRACT

The aim of this paper was to present the influence of temperature in the hydraulic behavior of Modified anaerobic baffled reactor (MABR). The MABR has seven compartments in which the first five compartments operate as anaerobic baffled reactor (ABR) followed by anaerobic filters (AF). Hydrodynamic behavior of the reactor was determined by calculating the residence time distribution (RTD). The RTD analyses was carried out by using tap water on clean reactor through tracer pulse input technique, to investigate compartment-wise variation of mean residence time, mixing patterns, dead spaces and hydraulic efficiency of the reactor at different temperatures with same hydraulic retention time (HRT). The reactor was run at two different temperatures: one normal water (25˚C) and another heated water (45˚C).The study results shown that the hydrodynamic characteristics of the reactor are not only depend on hydraulic retention time (HRT) but also temperature. The dead spaces generated by heated water in 1-, 2-, 3-, 4-, 5-, 6-, 7-compartment of the MABR were 35.9, 23.9, 17.7, 8.4, 2.4, 0 and 0%, respectively while the dead spaces generated by normal water in 1-, 2-, 3-, 4-, 5-, 6-, 7-compartment of the MABR were 44.8, 33.8, 27.5,14.3, 5.2, 0 and 0%, respectively. This indicates that the dead space decreased with the increase of temperature. In addition, increase of temperature the reactor compartments also resulted in the decrease in back-mixing. The dispersion number (D/uL) varies from 0.50 to 0.05 for heated water while dispersion number (D/uL) varies from 0.63 to 0.05 for normal water. The mixing pattern in compartment 1 and 2 showed a completely mixed type. On the other hand, the mixing behavior was intermediate between completely mixed and plug flow in 3-, 4-, 5-, 6-, 7-compartment of the MABR.

Keywords: *Back-mixing, Dead space, Hydraulic efficiency, Mean residence time, Modified anaerobic baffled reactor*

1. INTRODUCTION

The conventional septic tank is the oldest and the most popular mode of primary treatment method for onsite wastewater treatment. Due to some favorable economical and functional features, such a simple to design and operate, low cost to installation and minimum maintenance, septic tanks are the most popular option to treat onsite wastewater in such areas of the developing countries (Sharma and Kazmi, 2016). The main purpose of conventional septic tanks is to physically reduce suspended solids (SSs) and biologically remove dissolved organic compounds (Chen *et al*., 2014).

But there are several drawbacks associated with existing form of septic tank such as risk of explosion, low treatment efficiency and groundwater pollution, (Sharma *et al*., 2014) which may be attributed to its poor hydraulic characteristics and mixing pattern. The flow pattern in such system is in the horizontal direction. This hydraulic phenomenon will increase 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 and Kazmi, 2015).

Conventional septic tank systems are not effective in removing nitrate and phosphorus compounds and in reducing pathogenic organisms (Nasr and Mikhaeil, 2013). To overcome the issue, now a day, completely controlled reactors used for wastewater treatment. Among of them the Anaerobic Baffled Reactor (ABR) is a novel type of reactor was developed at Stanford University by McCarty and his co-workers to treat high strength wastewater. Conceptually, the ABR may be represented as a series of the up-flow anaerobic sludge blanket (UASB) reactors (Gopala Krishna *et al*., 2009). The ABR consists of a series of standing and vertical baffles that force the wastewater to flow under and over them as it passes from the inlet to outlet of the reactor. Biomass within the reactor gently rises with up-flowing and gas production in each compartment and settle down when no flow (Sarathai *et al*., 2010).

Last two decades, a successive of small modifications to existing reactor designs has enabled engineers to develop completely new reactor configurations, which allows high rates of hydraulic throughput with very little loss of biomass from the reactor, and a high reaction rate per unit volume. The ABR achieves this by means of a design

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which is both simple and cheap to construct, since there are no moving parts or mechanical mixing devices (Grobicki and Stuckey, 1992). Also the anaerobic baffled reactor has highly appraised for its high efficiency, outstanding working stability, and lower operating cost. The microbial alternation in the different compartments along the flow direction are realized that means it achieves high effective separation of acidogenesis and methanogenesis microbes longitudinally, and increasing the bacterial activity per unit volume of the reactor (Xu *et al*., 2014). The reactor have enabled to generate low sludge and high solids retention time (SRT 20-100 d), while keeping the hydraulic retention time (HRT) to a minimum (1.3-20 h) (Nachaiyasit and Stuckey, 1997; Langenhoff *et al*., 2000).

Another important feature that the degree of contact between the incoming substrate and the active biomass accumulated within the reactor is affected the treatment efficiency. Several studies have shown that the reactors filled with packing media or material undergo a greater biomass accumulation per unit volume of the reactor which also reduce the biomass wash out inside the reactor (Ladu and Lü, 2014). A biofilm is formed in the packing media that enhances the reproduction and growth of anaerobic bacteria. As wastewater flows through the filter, particles are trapped and organic matter is degraded by the biofilm which will increase the efficiency of contact between the substrate and microorganism. The supporting media also affects the HRT and the solid retention time both, which results in an increased treatment efficiency (Sharma and Kazmi, 2015). The physical properties such as specific surface area, porosity, surface roughness, pore size and orientation of the packing material (PM) are found to play an important role in the treatment efficiency and the hydraulic characteristics of the reactor. High specific surface area and porosity, large pore size and rough surface for PM allow for greater biomass accumulation and larger distribution of flow that improved the performance of the reactor (Elmitwalli *et al.*, 2000).

The treatment efficiency of an anaerobic process is highly dependent on temperature and hydrodynamic characteristics of the reactor. Reducing the operating temperature affects the performance. Lower substrate concentrations and reduced temperatures result in a deterioration of performance compared to higher substrate and increased temperature (Langenhoff and Stuckey, 2000). The treatment efficiency of organic matter has a maximum efficiency at 35–37ºC for mesophilic conditions and close to 55ºC for thermophilic conditions. Therefore, the performance of anaerobic processes is related to temperature, in a range of 10 to 45ºC and no important changes in the microbial ecosystem. Indeed, low temperatures reduce the hydrolysis performance (yield) and consequently the removal rate of total suspended solids (TSS) and, in general, the organic matter in the water is reduced (López-López *et al*., 2013). The hydrodynamic characteristics and degree of mixing that will occur within the reactor is strongly influenced the contract between substrate and bacteria that controlling the reactor performance (LIU *et al*., 2007). The flow patterns of the reactor greatly influence back-mixing, dead spaces, and hydraulic efficiency of the reactor which consequently affects treatment efficiency, working stability, and reaction time (Li *et al*., 2016). The effective use of the reactor volume and uniformity of environment for microorganisms depend on a good flow pattern. Therefore, to understand the performance of flow pattern of the ABR and the correlation between the flow pattern and back-mixing, dead spaces and volumetric efficiency then the engineering application of the ABR can be more efficiently realized (Xu *et al*., 2014).

So tracer experiments are 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 compartment-wise residence time, mixing pattern, dead spaces, and hydraulic efficiency of the reactor. Also investigate the temperature effects on these parameters.

2. MATERIALS AND METHODS

2.1 Experimental set-up

A laboratory scale reactor used in this experimental study was constructed with clear acrylic plastic (celluloid sheets). The dimension of each compartment is shown in table 1. 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 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 center of the up-flow chamber, thus achieving better contact and greater mixing of feed and biosolids. 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. In order to collect sample, sampling ports were provided at top of each chamber.

Table 1: Physical parameters of the ABR

Compartment	Length (cm)	Cumulative Length (cm)	Width (cm)	Effective Height (cm)	Volume (L)	Upflow / Down flow ratio
Compartment-1	22	22	20	25	11	4:1
Compartment-2	11	33	20	25	16.5	4:1
Compartment-3	11	44	20	25	22	4:1
Compartment-4	11	55	20	25	27.5	4:1
Compartment-5	11	66	20	25	33	4:1
Compartment-6	12	78	20	25	39	4:1
Compartment-7	12	90	20	25	45	4:1

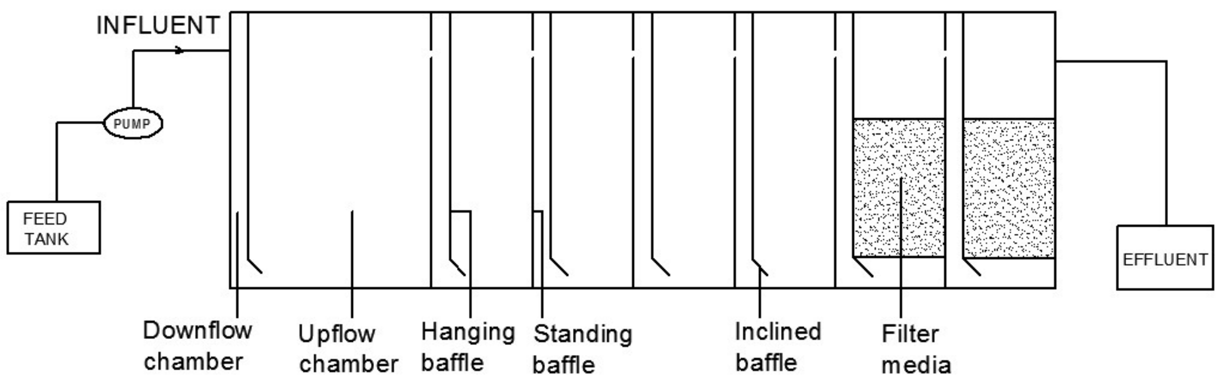

Figure 1: The schematic diagram of experimental setup.

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. The bottle cork was used as a filter media due to high specific surface area and high porosity. Also the bottle cork are locally available. The amount of bottle cork used in each chamber was 400gm. The figure 2 of shredded plastic bottle cork given below:

Figure 2: Filter media used in the study.

2.3 Experimental Design

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 analyzed for mixing pattern. Tracer studies were performed by using pulse input technique. Sodium chloride (NaCl) was selected as the tracer due to its various favorable 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).

2.4 Theoretical Interpretation

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:

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

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

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

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

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:

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

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

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

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

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

If $N = 1$, then the reactor approximated to the CSTR, and if $N = \infty$, 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 λ > 0.75;
ii. Satisfactory hydraulic efficiency with 0.5 < λ≤ 0.75; and
iii. Poor hydraulic efficiency where λ ≤ 0.5

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

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 DISCUSSION

3.1 HRT distribution of MABR

The hydraulic characteristics of the reactor were studied using the pulse input tracer test. The RTD studies were done to examine the mixing behavior of MABR at different temperatures. The normalized concentration of tracer was plotted against normalized time. Figure 3 shows that RTD curve of MABR for heated water and figure 4 shows that RTD curve of MABR for normal water.

As shown in the figure, the reactor residence time curve firstly rises and then drops, forming one single peak. In case of AF chamber, the distribution width of the RTD curves turned expended on the time axis due to the packed of anaerobic filter that might have influence the flow pattern. Further analysis of the RTD curves of reactor showed that, with the increase of temperature, the peak of the RTD curves decreased. This will directly effect on the hydraulic behavior of the reactor. All the resultant data are shown in table 2.

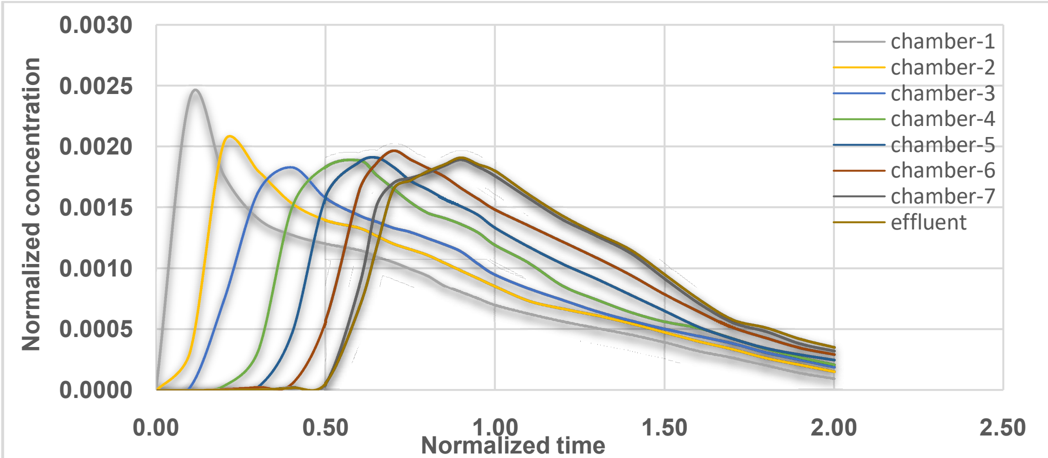

Figure 3: RTD graph of MABR for heated water

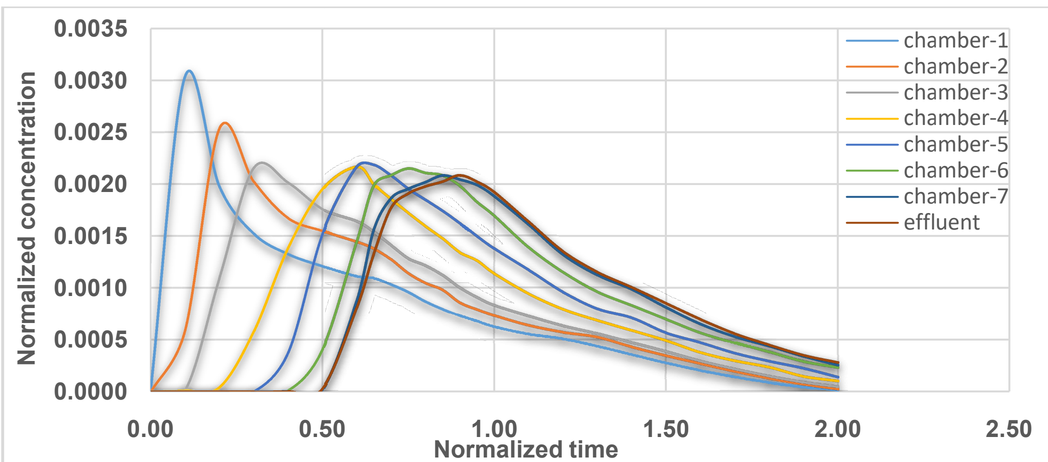

Figure 4: RTD graph of MABR for normal water.

Table 2: Hydraulic characteristics of MABR

Parameters	Normal water								Heated water							
	ch-1	ch-2	ch-3	ch-4	ch-5	ch-6	ch-7	Eff.	ch-1	ch-2	ch-3	ch-4	ch-5	ch-6	ch-7	Eff.
Mean residence time (min)	331	397	435	514	569	623	657	664	385	456	494	549	586	633	672	681
Dead space (%)	44.8	33.8	27.5	14.3	5.2	0	0	0	35.9	23.9	17.7	8.4	2.4	0	0	0
Dispersion number(D/uL)	0.63	0.28	0.19	0.11	0.08	0.06	0.05	0.05	0.5	0.25	0.18	0.11	0.09	0.07	0.05	0.05
No. of tank in series (N)	1.6	2.5	3.2	4.9	6.6	8.6	10.2	10.4	1.8	2.7	3.3	4.9	6.2	7.9	10.1	10.4
Hydraulic efficiency (λ)	0.21	0.39	0.5	0.68	0.8	0.88	0.9	0.9	0.28	0.47	0.58	0.73	0.82	0.87	0.9	0.9

3.2 Mixing patterns and hydraulic model

Mixing patterns are associated with the dimension variance obtained from the E-curve. Table 2 shows the hydraulic characteristics of MABR for both cases. The dispersion number of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the reactor were 0.63, 0.28, 0.19, 0.11, 0.08, 0.06, 0.05, and 0.05 for normal water and 0.50, 0.25, 0.18, 0.11, 0.09, 0.07, 0.05 and 0.05 for heated water, respectively. The first two chamber of the reactor approximates to single CSTR, as they has large dispersion number ($D/uL \geq 0.2$) implying a high degree of longitudinal mixing. The back-mixing becomes relatively weak for the rest of the chamber with dispersion numbers in the range $0.02 \leq D/uL \leq 0.2$, showing that the flow pattern is intermediate between completely mixed and plug flow which is an ideal condition for an effective treatment performance. Analysis of the hydraulic characteristics of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the MABR under the same operating conditions showed that, keeping the HRT value constant, the temperature has great impact on the mixing pattern of the MABR. The heated water shows better mixing pattern than normal water.

The tank-in-series model estimates the number of equal-sized stirred tanks (N), and N can be obtained from the reciprocal of the dimensionless variance from E-curve. The series numbers N of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the reactor were 1.6, 2.5, 3.2, 4.9, 6.6, 8.6, 10.2, and 10.4 for normal water and 1.8, 2.7, 3.3, 4.9, 6.2, 7.9, 10.1 and 10.4 for heated water, respectively. From the results obtained, it is clear that the flow pattern approaches PF when $N \rightarrow \infty$, and the flow pattern tends to approach completely mixed flow when $N \rightarrow 1$. Thus, back-mixing predicted by the tank-in-series model showed the same tendency as predicted by the axial dispersion model.

3.3 Dead space

Dead space in the reactor can be generally divided into hydraulic dead space and biological dead space. But in this study, tap water was used to analyze the hydrodynamic characteristics. So only hydraulic dead space was calculated in this study. The dead space is produced by short circuiting and channeling effect which hinder the successful design of the reactor. The percentages of dead space of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the reactor were 44.8, 33.8, 27.5, 14.3, 5.2, 0, 0, and 0 for normal water and 35.9, 23.9, 17.7, 8.4, 2.4, 0, 0 and 0 for heated water, respectively shown in figure 5. The temperature has also impact on the dead space of the reactor. The heated water produced less dead space than normal water.

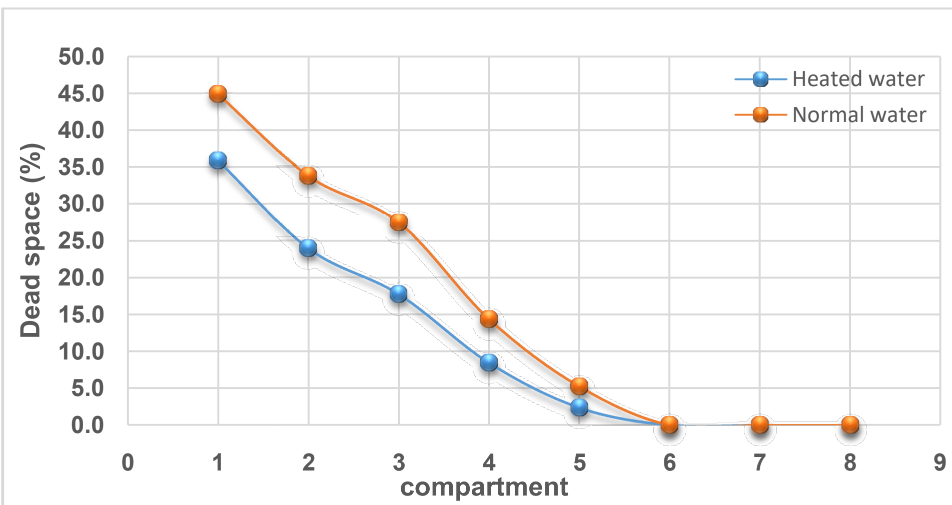

Figure 5: Percentages of dead space in the reactor at normal water and heated water.

3.4 Hydraulic Efficiency

The performance of the hydraulic efficiency is associated with the effective volume and flow pattern; hence on the one hand, it is related to the working performance of the reactor, and on the other hand, it is influenced by hydraulic characteristics. The hydraulic efficiency of 1-, 2-, 3-, 4-, 5-, 6-, 7-chamber and effluent of the reactor were 0.21, 039, 0.50, 0.68, 0.80, 0.88, 0.90, and 0.90 for normal water and 0.28, 0.47, 0.58, 0.73, 0.82, 0.87, 0.90 and 0.90 for heated water, respectively shown in figure 6. Persson *et al.* (1999) classified the hydraulic efficiency into three category: good ($\lambda > 0.75$), Satisfactory ($0.5 < \lambda \leq 0.75$), Poor ($\lambda \leq 0.5$). The hydraulic efficiency of MABR was good at 5-, 6-, and 7- chamber and Satisfactory at 3-, 4-chamber but worse at 1-, 2-chamber. In the case of anaerobic filter, the hydraulic efficiency falls under the category of good. Further analysis of reactor showed that, with the increase of temperature, better hydraulic performance was achieved. Thus, the hydraulic efficiency represents the ability of the system to distribute its flow uniformly throughout its volume, maximizing the contact time of pollutant in the system and optimizing the ability to break down the pollutants.

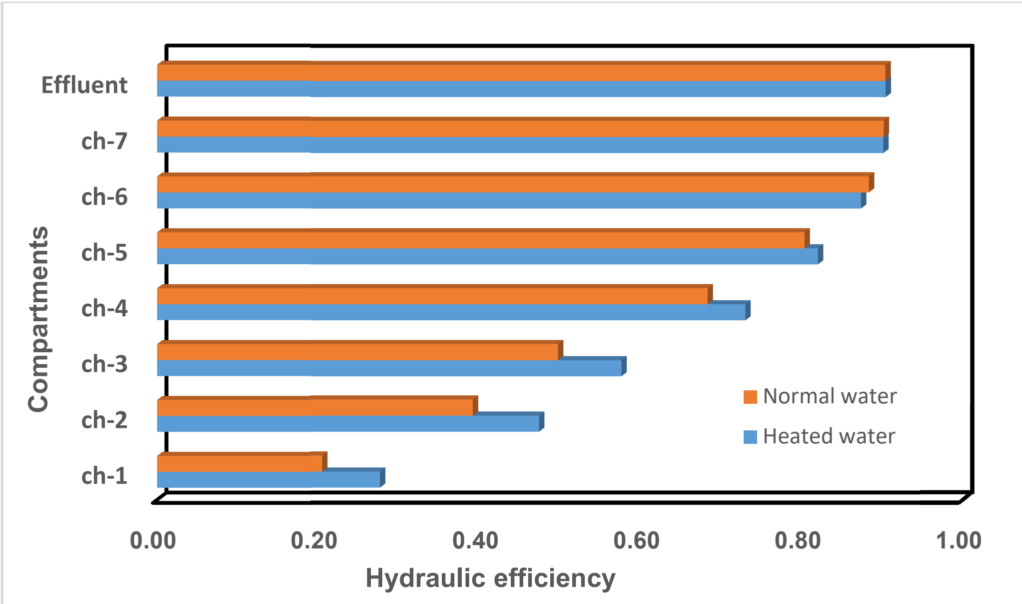

Figure 6: Performance of hydraulic efficiency at normal water and heated water.

3. CONCLUSIONS

In this study, the hydrodynamic of the MABR was studied at two different temperatures. Though MABR was a combined reactor (ABR followed by AF), the performance of anaerobic filter (AF) is better than anaerobic baffled reactor (ABR).

- Hydrodynamic study revealed that, the first two chambers were single CSTR and the rest of the chambers were intermediated between PF and CSTR. Besides the increase of temperature, the better mixing pattern was achieved.
- The dead space decrease with increase the number of chamber. In the last two chambers, the dead space was zero due to the effect of filter media. The temperature has also impact on the dead space of the MABR. The normal water produces 33% more dead space than heated water.
- The hydraulic efficiency increase with the increase of ABR compartments. Good hydraulic performance was observed in last three compartments and satisfactory performance in the middle compartments.
- Taking the operating performance and economic factors of the reactor into full consideration, the present study recommends that the series number (N) of MABR compartments shall be kept at least 6.

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REFERENCES

Chen, Z., Wen, Q., Guan, H., Bakke, R., and Ren, N., 2014. Anaerobic treatment of domestic sewage in modified septic tanks at low temperature, *Environmental Technology*, *35*(17), 2123–2131.

Elmitwalli, T. A., Van Dun, M., Bruning, H., Zeeman, G., and Lettinga, G., 2000, The role of filter media in removing suspended and colloidal particles in an anaerobic reactor treating domestic sewage, *Bioresource Technology*, *72*(3), 235-242.

Gopala Krishna, G. V. T., Kumar, P., and Kumar, P., 2009. Treatment of low-strength soluble wastewater using an anaerobic baffled reactor (ABR), *Journal of Environmental Management*, *90*(1), 166–176.

Grobicki, A., and Stuckey, D. C., 1992. Hydrodynamic characteristics of the anaerobic baffled reactor, *Water Research*, *26*(3), 371–378.

Ladu, J. L. C., and Lü, X., 2014. Effects of hydraulic retention time, temperature, and effluent recycling on efficiency of anaerobic filter in treating rural domestic wastewater, *Water Science and Engineering*, *7*(2), 168–182.

Langenhoff, A. A., Intrachandra, N., and Stuckey, D. C., 2000. Treatment of dilute soluble and colloidal wastewater using an anaerobic baffled reactor: influence of hydraulic retention time, *Water Research*, *34*(4), 1307–1317.

Li, S., Nan, J., and Gao, F., 2016. Hydraulic characteristics and performance modeling of a modified anaerobic baffled reactor (MABR), *Chemical Engineering Journal*, *284*, 85–92.

LIU, X., REN, N., and WAN, C., 2007. Hydrodynamic characteristics of a four-compartment periodic anaerobic baffled reactor, *Journal of Environmental Sciences*, *19*(10), 1159–1165.

López-López, A., Albarrán-Rivas, M. G., Hernández-Mena, L., and León-Becerril, E., 2013. An assessment of an anaerobic filter packed with a low-cost material for treating domestic wastewater: *Environmental Technology*, *34*(9), 1151–1159.

Nachaiyasit, S., and Stuckey, D. C., 1997. The effect of shock loads on the performance of an anaerobic baffled reactor (ABR). 1. Step changes in feed concentration at constant retention time. *Water Research*, *31*(11), 2737–2746.

Nasr, F. A., and Mikhaeil, B., 2013. Treatment of domestic wastewater using conventional and baffled septic tanks, *Environmental Technology*, *34*(16), 2337–2343.

Sarathai, Y., Koottatep, T., and Morel, A., 2010. Hydraulic characteristics of an anaerobic baffled reactor as onsite wastewater treatment system, *Journal of Environmental Sciences*, *22*(9), 1319–1326.

Sharma, M. K., and Kazmi, A. A., 2015. Effect of physical property of supporting media and variable hydraulic loading on hydraulic characteristics of advanced onsite wastewater treatment system, *Environmental Technology*, *36*(11), 1414–1422.

Sharma, M. K., and Kazmi, A. A., 2016. Performance evaluation of a single household anaerobic packaged system for onsite domestic wastewater treatment, *Desalination and Water Treatment*, *57*(20), 9216–9225.

Sharma, M. K., Khursheed, A., and Kazmi, A. A., 2014. Modified septic tank-anaerobic filter unit as a two-stage onsite domestic wastewater treatment system, *Environmental Technology*, *35*(17), 2183–2193.

Xu, M., Ding, L., Xu, K., Geng, J., and Ren, H., 2014. Flow patterns and optimization of compartments for the anaerobic baffled reactor, *Desalination and Water Treatment*, 1–8.