# Evaluation of the factors affecting hydrodynamic characteristics of a hybrid anaerobic baffled reactor

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**The residence time distribution was used to study the hydrodynamic behaviour using the pulse input tracer technique. The effect of medium, compartment-wise variation in the mixing patterns inside the reactor and hydraulic retention time on the hydrodynamic characteristics of the reactor was studied. The influence of the number of compartments was predominant compared to the hydraulic retention time and presence of a medium. The flow regime in the first, second and third compartments was in the intermediate state whereas the flow regime was in plug-flow state in the rear compartment. The interactive effects were evaluated using response surface methodology.**

**Keywords:** Anaerobic baffled reactor, dead space, hydraulic efficiency, residence time distribution, response surface methodology.

MAJOR issues like water crisis, deterioration of surface water and the depletion of underground water resources lead to the reuse and recycling of wastewater. Thus the need for technical and economically viable technology for wastewater treatment to satisfy the water needs and meet the stringent regulations for wastewater discharge arises. Anaerobic treatment, combined with other treatment methods, has emerged as an advanced technology for the protection of the environment and resources, especially in developing countries. The anaerobic baffled reactor (ABR) is an innovative reactor design to implement the anaerobic technology. ABR has several compartments that force the wastewater to flow under and over the vertical baffles arranged from the inlet to outlet[1]. This makes a large amount of active biomass come into intimate contact with the wastewater to increase the efficiency of the reactor[2]. The advantages of the ABR are: (i) construction aspects like simple design, reduced clogging, low capital and operating cost, no moving parts, no mechanical mixing, and (ii) biomass aspects like low sludge production, high solid retention time, retention of biomass without fixed media, and (iii) operation aspects like low hydraulic retention time (HRT) and being stable to organic shock. One of the disadvantages of conventional ABR is poor effluent quality. Usually, post-treatment aerobic systems are combined with the ABR to meet the effluent sewage discharge limits[3]. In recent decades, the ABR has been modified and combined with other aerobic processes to increase domestic, industrial and refractory wastewater treatment efficiency. The hydrodynamics and degree of mixing significantly impact the contact between the biomass and substrate. Thus, the efficiency of the reactor is strongly influenced by its hydrodynamic behaviour[4]. The completely mixed condition lowers the treatment efficiency in the reactor due to high mixing[5]. In contrast, the unstirred plug-flow condition decreases the treatment performance by the accumulation of organic acids by lowering the pH (ref. 1). Thus, the intermediate state between the plug flow and the completely mixed condition provides the highest treatment efficiency. This intermediate state can be achieved through several factors such as recycling, variation in HRT, fluid channelling by forming dead zones, geometrical changes in the reactor, or a combination of all these factors. In the present study, the flow regime was varied by changing HRT, increasing the number of compartments and some geometrical changes in the reactor to achieve maximum treatment efficiency by studying its hydrodynamic behaviour. Response surface methodology (RSM) was used with respect to the simultaneous effect of two independent variables (HRT and the number of compartments) to study the interactive effects of four inter-related parameters as responses.

## Materials and methods

### *Experimental set-up*

The hybrid anaerobic baffled reactor (HABR) used in this study was made of acrylic material and consisted of four compartments of length, breadth, height 500, 400 and 500 mm respectively, and a working volume of 100 litres. The volume of the first three compartments was 20 litre (length 100 mm, breadth 400 mm and height 500 mm) and that of the fourth compartment was 40 litre (length 200 mm, breadth 400 mm and height 500 mm). The hanging baffles were used in the individual compartments form up-flow and down-flow chambers in the ratio 1 : 4. Each

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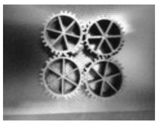
**Table 1.** Characteristics of the different media

| Material | Polypropylene | Polypropylene | Polyethylene |
|---|---|---|---|
| Outer diameter (mm) | 20 | 10 | 60 |
| Inner diameter (mm) | 18 | 8 | – |
| Height (mm) | 14.5 | 7 | – |
| Density (g/cm³) | 0.97 | 0.98 | 0.96 |
| Specific surface area ($m^2/m^3$) | 500 | 680 | 1000 |
| Colour | Black | White | White |
| Image |  |  |  |

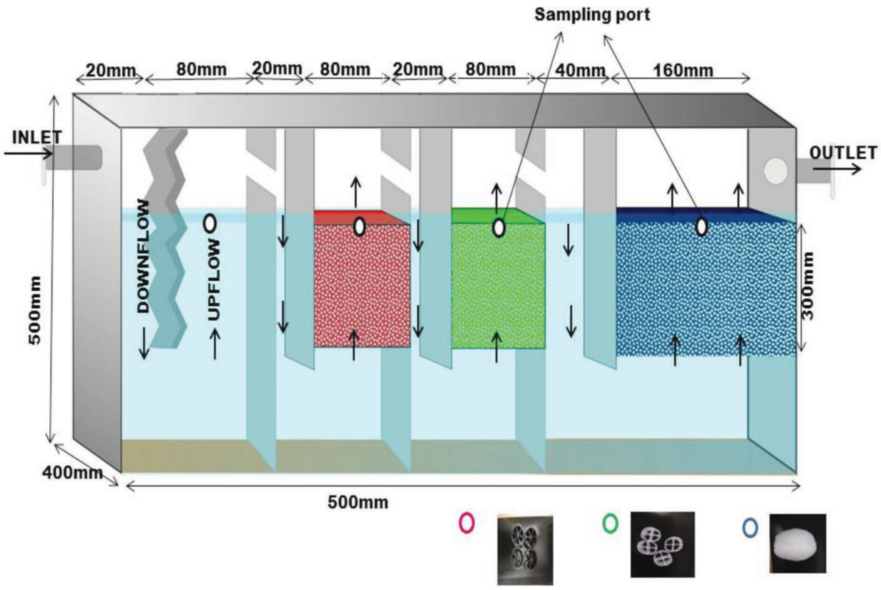



**Figure 1.** Schematic diagram of the hybrid anaerobic baffled reactor.

chamber had a sampling port located 15 cm from the top. The first chamber acted as a normal settling chamber, whereas the second, third and fourth compartment up-flow chambers were filled with different media. The second and fourth chambers were fully packed with medium up to the height of 30 cm, while in the third chamber, 40% of the volume was filled with medium. Table 1 shows the characteristics of different media. The hanging baffle in the first compartment was designed in a zig-zag manner. Figure 1 shows the schematic diagram of the HABR.

## *Experimental procedure*

In the first stage, residence time distribution by tracer stimulus-response technology was used to study the hydraulic characteristics of the reactor. Ponceau 4R was used as the tracer throughout the study because it will not be absorbed nor react with the substances inside the reactor[6]. The maximum absorbance of Ponceau 4R was at 508 nm (ref. 7). The tracer was injected as pulse input within 10 sec into the inlet. Then the samples were collected at constant interval of time of about two times the hydraulic retention time, in all four compartments. They were absorbed using a UV–visible spectrophotometer at 508 nm and the residence time distribution (RTD) curves were drawn for all four compartments. The above procedure was carried out in the HABR with and without medium by varying HRT (4, 8 and 12 h). The hydrodynamic indices were calculated using the axial dispersion model and tanks in series model with reference to Table 2 (refs 1, 3, 8–15).

In the second stage, the values obtained from all the runs were evaluated using RSM by central composite design (CCD). Here, CCD was used to study two parameters (HRT and the number of compartments) to evaluate four different responses.

## Results and discussion

## *RTD study*

RTD was used to study the hydraulic characteristics of the reactor. The RTD curves plot the normalized concentration

**Table 2.** Hydrodynamic indices

| Parameters | Equation | Reference |
|---|---|---|
| Mean cell residence time ($\tau$) | $\tau = \int_0^\infty tC(t)\mathrm{d}t$ | 1, 8–11 |
| Variance ($\sigma_m^2$) | $\sigma_m^2 = \int_0^\infty t^2C(t)\mathrm{d}t - \tau^2$ | 1, 8–11 |
| Dispersion number ($d$) | $D = D/uL$ | 3, 9, 12 |
| Number of continuous stirred tanks in series ($N$) | $N = 1/\sigma_0^2$ | 12 |
| Hydraulic efficiency ($\lambda$) | $\lambda = e(1-(1/N))$ | 12–15 |

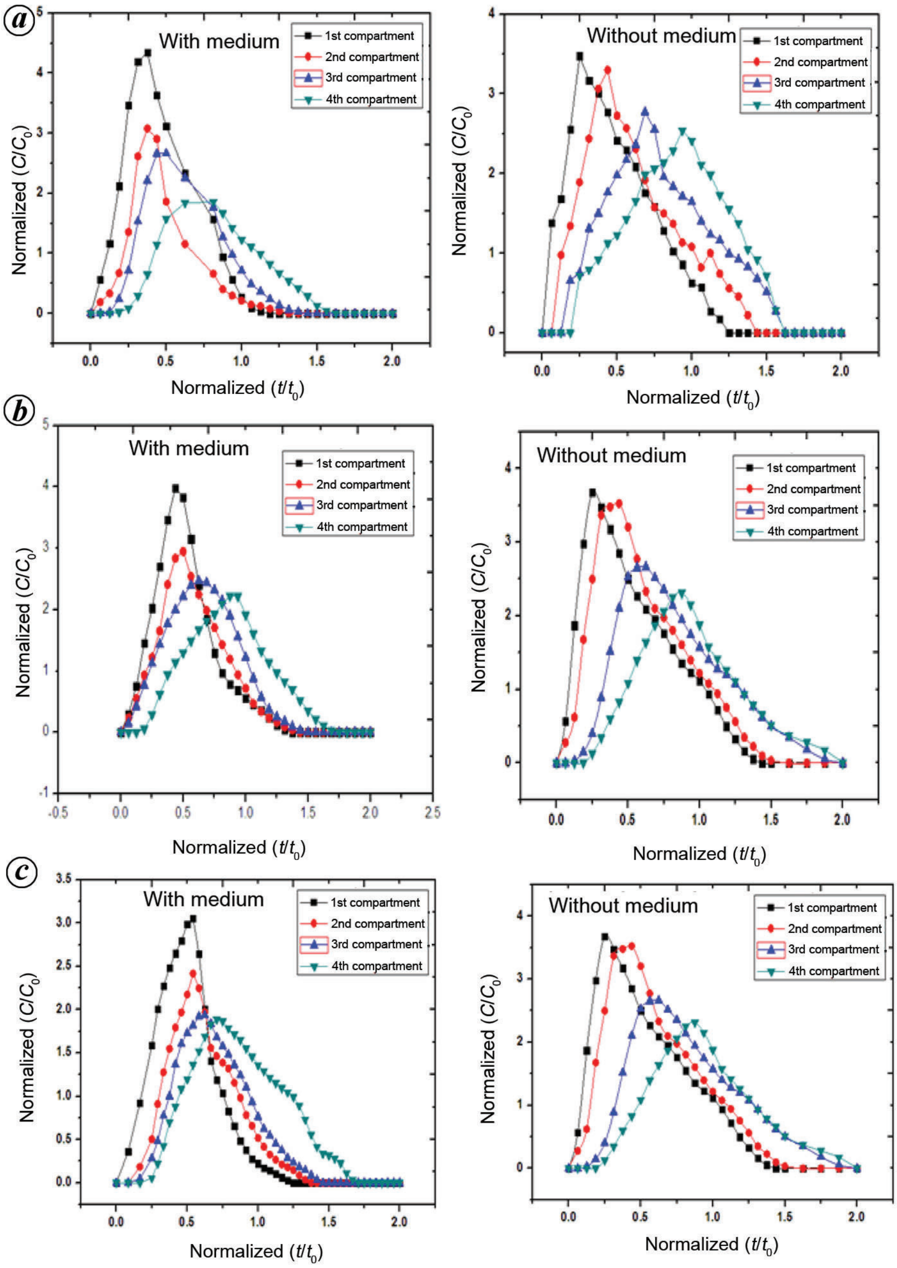



**Figure 2.** Residence time distribution curves of anaerobic baffled reactor at (***a***) 4 h, (***b***) 8 h and (***c***) 12 h.

against normalized time. Figure 2 *a–c* shows the RTD curves of HABR with and without medium at different HRTs in all compartments. The normalized concentration drastically increases with respect to normalized time and after reaching a maximum value the curve starts decreasing.

The peak of normalized concentration appeared at $\theta = 0.4 \pm 0.1$ and $\theta = 0.5 \pm 0.1$ in HABR with and without a medium in the second compartment, and at $\theta = 0.8 \pm 0.1$ and $\theta = 0.9 \pm 0.1$ in the rear compartment. Thus, it is evident that, a higher value of the tail area in HABR in the initial compartments leads to an increase in dead space[16,17]. From Figure 2 *a–c*, it can be observed that the tail area decreases as HRT increases, which also resulted in a decrease in dead space by increasing HRT. Overall, there was only a marginal difference in RTD peaks by varying HRTs and medium inside the reactor. However, there was a significant difference in the RTD peaks by varying the number of compartments in the reactor. Thus this is the key factor influencing the hydrodynamic behaviour of the reactor[3].

### *Dead space*

The total dead space of HABR is the sum of hydraulic dead space and biological dead space. The flow rate and the number of compartments influenced the hydraulic dead space, whereas biological dead space was influenced by the biomass[1,18]. The addition of sludge inside the reactor had a meagre influence on the biological dead space. Thus, the hydraulic dead space contributed more to the total dead space[19,20]. In this study, the hydraulic dead space was estimated for HABR by varying parameters like the number of compartments, presence of medium and HRT. The dead space ($V_d$) in the reactor is given below

$$V_d\,(\%) = (1 - (\tau/\text{HRT})) \times 100. \quad (1)$$

From Figure 3, it can be observed that the dead space ranged from 58.3% to 6.4%. The higher value of dead space in the first compartment for 4 h HRT was due to the channelling effect in the reactor. The channelling causes stagnant eddies

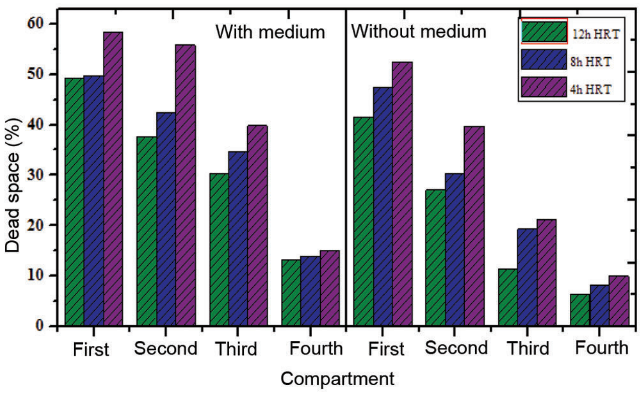



**Figure 3.** Variation of dead space under different conditions.

formation under weirs and in the corners of the reactor. These eddies act as reservoirs where the tracer slowly diffuses in and out of the reactor[3]. The pattern of increase in dead space by decreasing HRT and the number of compartments was observed to be the same in HABR with and without media. The value of dead space was slightly higher in HABR with a medium (58.3–13.3%) due to the hindrance of the medium, than in HABR without medium (52.5–6.4%). Hence, the volume of reactor with presence of medium is effectively used as the reactor without a medium. Figure 3 shows that the number of compartments was the primary factor in creating dead space, as the decrease in dead space was more by increasing the number of compartments compared to increasing HRT.

### *Hydraulic models*

To increase the treatment efficiency in the reactor, it is necessary to study the flow pattern inside the reactor. The state of flow condition in the reactor was determined using various models with the help of hydraulic indexes found.

*Axial dispersion model:* Table 3 shows the dispersion number ($d$) obtained from the axial dispersion model by varying HRT and the number of compartments. By increasing the number of compartments and HRT, the value $d$ can be decreased. The lower value of $d$ in ABR with the medium was due to hindrance, which lowered dispersion inside the reactor. A hydrodynamic study of an eight-chambered ABR showed that the flow pattern was intermediate between completely mixed flow and plug flow[3,19]. However, as HRT or the number of compartments increased, the reactor behaved like a plug-flow reactor. Likewise, for all the runs, the $d = (D \mid uL)$ values were $0.2 > d > 0.002$, which led to large dispersion and was intermediate between mixed-flow and plug-flow conditions in most of the chambers. However, with an increase in HRT, there was a decrease in the flow rate resulting in less back mixing, propelling the reactor closer to plug-flow condition.

*TIS model:* Table 3 also shows the number of tanks in series ($N$) obtained from the tanks in series model and hydraulic efficiency ($\lambda$). As HRT increases, the $N$ value increases, propelling the reactor towards the plug-flow condition. For all the runs, the $N$ values of the first and second compartments mostly lie between 3 and 4, approaching the reactor intermediate between completely stirred tank reactor (CSTR) and plug flow. The $N$ values of the third and fourth compartments are >4 (8.47 to 5.51), indicating in plug-flow condition. When comparing the dispersion number ($d$) and the number of tanks in series ($N$), there was a major difference in the values between compartments and a small difference in values when there was a variation in HRT and the presence and absence of a medium. Thus from the axial dispersion model and tanks in the series model, it is evident

**Table 3.** Indices obtained from the axial dispersion model

| Compartment | HRT (h) | Mean retention time ($\tau$; h) | Dispersion number ($d$) | Number of tanks in series ($N$) | Hydraulic efficiency ($\lambda$) |
|---|---|---|---|---|---|
| 1(1) | 12 | 7.01 | 0.157 | 3.78 | 0.43 |
| 1(2) | 12 | 6.10 | 0.077 | 7.04 | 0.43 |
| 2(1) | 12 | 8.76 | 0.097 | 5.71 | 0.60 |
| 2(2) | 12 | 7.48 | 0.068 | 7.87 | 0.54 |
| 3(1) | 12 | 10.64 | 0.068 | 7.87 | 0.77 |
| 3(2) | 12 | 8.35 | 0.063 | 8.47 | 0.61 |
| 4(1) | 12 | 10.40 | 0.066 | 8.13 | 0.82 |
| 4(2) | 12 | 6.40 | 0.063 | 8.47 | 0.76 |
| 1(1) | 8 | 4.20 | 0.192 | 3.22 | 0.36 |
| 1(2) | 8 | 4.10 | 0.119 | 5.00 | 0.41 |
| 2(1) | 8 | 4.77 | 0.147 | 4.00 | 0.44 |
| 2(2) | 8 | 4.61 | 0.101 | 5.49 | 0.47 |
| 3(1) | 8 | 6.45 | 0.088 | 6.25 | 0.67 |
| 3(2) | 8 | 5.23 | 0.085 | 6.45 | 0.55 |
| 4(1) | 8 | 6.88 | 0.067 | 8.06 | 0.80 |
| 4(2) | 8 | 8.20 | 0.064 | 8.33 | 0.76 |
| 1(1) | 4 | 1.90 | 0.195 | 3.17 | 0.32 |
| 1(2) | 4 | 1.67 | 0.140 | 4.17 | 0.32 |
| 2(1) | 4 | 2.41 | 0.152 | 3.88 | 0.44 |
| 2(2) | 4 | 1.77 | 0.126 | 4.54 | 0.34 |
| 3(1) | 4 | 3.15 | 0.100 | 5.51 | 0.64 |
| 3(2) | 4 | 2.41 | 0.100 | 5.55 | 0.49 |
| 4(1) | 4 | 3.60 | 0.068 | 7.93 | 0.79 |
| 4(2) | 4 | 3.40 | 0.067 | 8.06 | 0.75 |

(1) Anaerobic baffled reactor (ABR) without medium and (2) ABR with medium.

**Table 4.** ANOVA results obtained from response surface methodology

| Response | Equation | $R^2$ | Adj $R^2$ | Pred $R^2$ | AP | CV% | $F$-value | $P$-value |
|---|---|---|---|---|---|---|---|---|
| Dead space | $+ 73.25 - 2.00A - 8.50B + 0.35AB - 3.516E - 003A^2 - 1.45B^2$ | 0.869 | 0.833 | 0.788 | 14.31 | 21.23 | 24.06 | <0.0001 |
| Dispersion number | $+ 0.24 - 2.219E - 003A - 0.06B + 2.056E - 003AB - 4.648E{-}004A^2 + 3.333E{-}003B^2$ | 0.750 | 0.681 | 0.497 | 10.11 | 22.71 | 10.84 | <0.0001 |
| Number of tanks in series | $+ 2.21 - 0.05A + 0.91B - 0.053AB + 0.026A^2 + 0.16B^2$ | 0.815 | 0.764 | 0.634 | 12.54 | 14.68 | 15.89 | <0.0001 |
| Hydraulic efficiency | $+ 0.14 + 0.016A + 0.087B - 4.063E - 003AB - 5.078E - 004A^2 + 0.016B^2$ | 0.920 | 0.898 | 0.870 | 19.02 | 9.62 | 14.59 | <0.0001 |

$A$, HRT (h); $B$, chambers. + denotes the positive value of the numerical. AP, Adequate precision; CV, Coefficient of variation; Pred, Predicted; Adj, Adjusted; $E = 10^{-6}$.

that the number of compartments is the primary factor influencing the hydraulic characteristics in HABR.

The hydraulic efficiency explains the uniform distribution of flow within the reactor, optimum treatment efficiency and the maximum contact time of the pollutant in the reactor[3,9]. From Table 3, it is evident that the flow has good hydraulic efficiency with $\lambda > 0.75$ in the fourth compartment under all conditions, while in the third compartment the flow has moderate hydraulic efficiency with $0.75 < \lambda \geq 0.5$. In the first and second compartments $\lambda < 0.5$ and the flow has poor hydraulic efficiency.

## *Statistical analysis*

RSM had many classes like CCD Box–Behnken design, hybrid design and three-level factorial design. CCD is the most frequently used RSM design. In this study, the relationship between the variables (HRT and the number of chambers) and hydraulic responses like dead space, dispersion number, hydraulic efficiency and the number of tanks in series was found using RSM. Experimental data obtained from three runs in HABR with media and without medium were analysed by RSM. Here, HRTs 4, 8 and 12 h, and chambers 1–4 were used as the independent factors in RSM. CCD was used to develop a quadratic model for each response such as dead space, hydraulic efficiency, dispersion number and the number of tanks in series to quantify the curvature effects for the responses[20]. Table 4 shows the ANOVA results for the responses.

The significance of the model was determined by the $F$-value and values of probability $>F$. The probability $>F$ of value less than 0.05 indicated that the model terms were

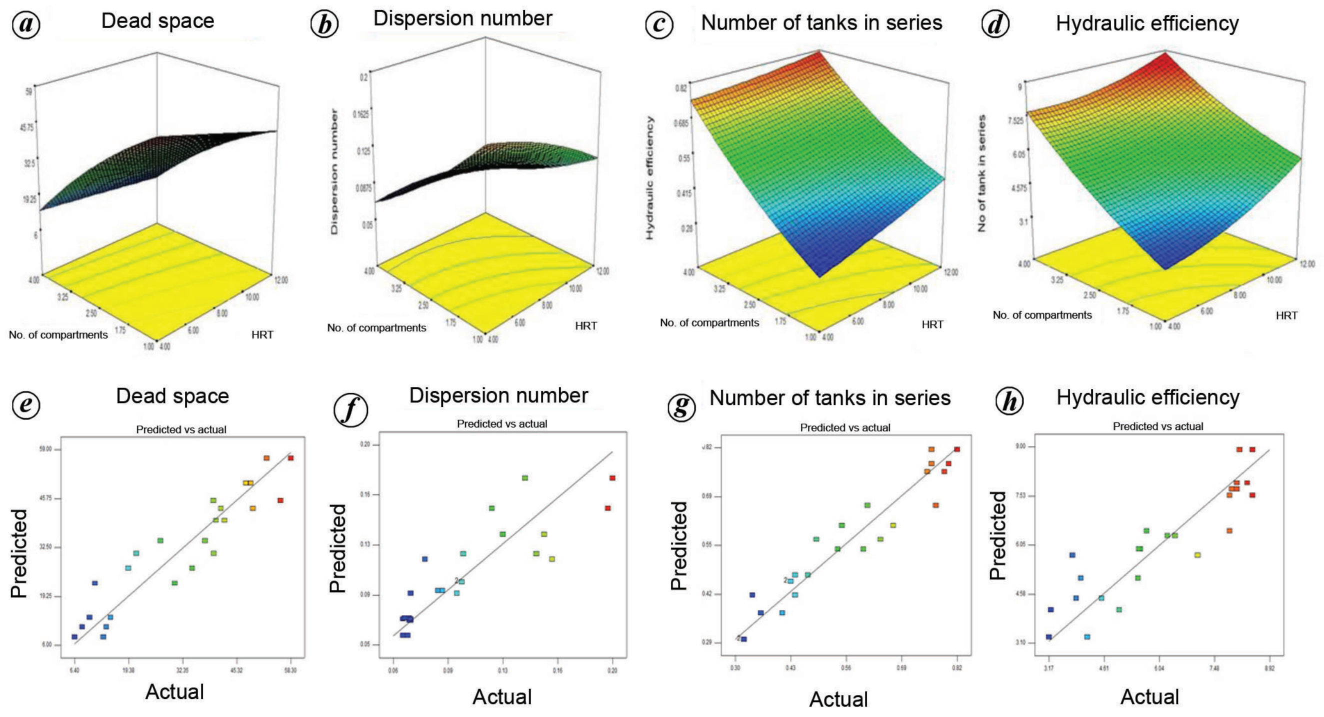



**Figure 4.** (***a–d***) Surface and contour plots and (***e–h***) predicted versus actual values of responses.

statistically significant. In Table 4, the *P*-value (the value of probability) was <0.0001, showing that the independent variables were significant at a 95% confidence level. The model *F*-value of dead space, dispersion number, number of tanks in series and hydraulic efficiency were 24.06, 10.84, 15.89 and 14.59 respectively; these values imply that the model used in the statistical analysis was found significant. Adeq precision (AP) measured the signal-to-noise ratio with a value greater than 4 was desirable. The AP values of 14.31 for dead space, 10.11 for dispersion number, 12.54 for the number of tanks in series and 19.02 for hydraulic efficiency indicate adequate signals. The pred $R^2$ values of 0.788 for dead space, 0.497 for dispersion number, 0.634 for the number of tank in series, 0.870 for hydraulic efficiency were in reasonable agreement with the adj $R^2$ values were 0.833 for dead space, 0.681 for dispersion number, 0.764 for the number of tanks in series and 0.898 for hydraulic efficiency. Figure 4 *e–h* shows good convergence between the actual (experimental) and predicted (model) values for dead space, dispersion number, number of tanks in series and hydraulic efficiency. The actual values are distributed closer to the straight line. The $R^2$ and adj $R^2$ value of experimental and model predicted were close to 1.0 which shows that the model is significant. Hence the fit of the model was verified and there was good consistency between the actual and predicted values of response surface assessment[20]. The lower values of coefficient of variation (CV; 9.62–22.71%) indicated reliability and good precision of the experiments. Figure 4 *a–d* shows the combined effects of HRT and different chambers on the dead space, dispersion number, number of tanks in series and hydraulic efficiency in HABR. It can be observed that the dead space is primarily influenced by the number of chambers rather than HRT. As the number of chambers increases, the dead space decreases. Hence, from the curvature effect of responses, it can be proved that the number of compartments is the primary factor influencing the hydraulic characteristics.

## Conclusion

The dead space decreased with an increase in HRT and the number of compartments. The dead space in ABR with and without medium showed only a marginal difference (within 0.5%). The results reveal that the number of compartments in the reactor has a greater influence on its performance and the creation of dead space compared to HRT time and the presence of medium. The hydrodynamic characteristics studied by axial dispersion and the TIS model to determine the state of condition in the reactor showed that the first, second and third compartments were intermediate between CSTR and plug-flow conditions. This condition results in higher treatment efficiency in ABR with and without medium. The ABR showed good hydraulic efficiency after the third compartment with $\lambda > 0.75$ by varying HRT. Hence the proposed ABR with and without medium works well with four compartments and can be effectively used to treat low-strength, high-strength and refractory wastewater. Due to the advantage of the presence of medium by increasing the biomass contact with the substrate and the fact that the medium creates only a small dead space compared to ABR without medium, the proposed ABR with medium has higher treatment efficiency compared to ABR without medium. CCD analysis using RSM determines the interactive effects on the hydraulic responses like dead space, dispersion number, the number of tanks in series and hydraulic efficiency.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ACKNOWLEDGEMENT. We acknowledge the financial support received from Anna University through Anna Centenary Research Fellowship for carrying out this work.

Received 25 February 2021; revised accepted 8 October 2022

doi: 10.18520/cs/v124/i2/176-182