

High-rate Wastewater Treatment by a Shaft-type Activated Sludge Reactor

Subrata Hait and Debabrata Mazumder

Abstract—A shaft-type activated sludge reactor has been developed in order to study the feasibility of high-rate wastewater treatment. The reactor having volume of about 14.5 L was operated with the acclimated mixed activated sludge under batch and continuous mode using a synthetic wastewater as feed. The batch study was performed with varying chemical oxygen demand (COD) concentrations of 1000–3500 mg·L⁻¹ for a batch period up to 9 h. The kinetic coefficients: K_s , k , Y and k_d were obtained as 2040.2 mg·L⁻¹ and 0.105 h⁻¹, 0.878 and 0.0025 h⁻¹ respectively from Monod's approach. The continuous study showed a stable and steady state operation for a hydraulic retention time (HRT) of 8 h and influent COD of about 1000 mg·L⁻¹. A maximum COD removal efficiency of about 80% was attained at a COD loading rate and food-to-microorganism (F/M) ratio (COD basis) of 3.42 kg·m⁻³·d⁻¹ and 1.0 kg·kg⁻¹·d⁻¹ respectively under a HRT of 8 h. The reactor was also found to handle COD loading rate and F/M ratio of 10.8 kg·m⁻³·d⁻¹ and 2.20 kg·kg⁻¹·d⁻¹ respectively showing a COD removal efficiency of about 46%.

Keywords—Activated sludge process, shaft-type reactor, high-rate treatment, carbonaceous wastewater.

I. INTRODUCTION

THE activated sludge process (ASP) is the most common and versatile biological process used worldwide for the secondary treatment of domestic, municipal and industrial wastewater. With the course of time, several modifications of the ASP have been made to improve the degree of treatment in accordance with stringent effluent standards. Optimization was also brought into account to reduce the establishment and operating costs of wastewater treatment plant. Some of the modifications are capable of providing high-rate treatment with low to moderately low organic loads, but they are not satisfactory for high organic loads. This is because of limitation of oxygen availability due to poor transfer efficiency from the air supplied, which is essential for aerobic decomposition [1]. Another crucial problem related with conventional ASP is the requirement of relatively large land area.

To resolve these problems, a deep-shaft modification of the ASP was developed in the 1970s by Imperial Chemical

Industries (ICI) introducing a deep-shaft or well, normally 50 to 150 m deep and 5 to 6 m wide, along with suitable recirculation of microorganisms [2]. The key feature of the shaft-type reactor is the higher depth compared to the width, which ensures higher partial pressure of oxygen at the base of the unit, resulting in high oxygen transfer efficiency (OTE). Literatures reveal that oxygen transfer efficiency of 4–20% in conventional activated sludge system can be increased to as high as 90% in case of deep-shaft activated sludge system [3]. The relationships between the gas velocity, liquid circulation velocity, depth of air introduced and oxygen utilization along with the power economy of the deep-shaft aerator have been discussed elsewhere [4]. The absorption and the transfer capability of oxygen in the deep-shaft activated sludge process can substantially be enhanced with an increase in aeration rate at a fixed water depth and the tank width respectively [5]. Moreover, it has a small space requirement, taking up 50% less land area than conventional ASP because this process does not require primary sedimentation unit and the aeration tank being mainly semi-underground [6]. The general biological aspects of deep-shaft process of wastewater treatment have been explained in detail [7]. Deep-shaft wastewater treatment technology is said to be potential to resist shock loads [8]. An improvement of settleability of sludge, separation of sludge and supernatant with good carbonaceous oxidation at relatively low power requirement in the shaft-type reactor has also been demonstrated [9]. Different aspects of deep-shaft bioreactors with respect to advantages in design, operation and performance in wastewater treatment have also been discussed in detail [10]. Deep-shaft configuration can be regarded as suitable alternative of upgrading a conventional activated sludge plant with good carbonaceous oxidation performance [9], [11]. It has been proved that this system is capable of providing high degradation rate of carbonaceous matter with excellent use of oxygen [12].

Deep-shaft technology has proven highly competitive and versatile in treating municipal and industrial effluents as it involves low power consumption and land requirement. It has been successfully applied to treat municipal wastewater (MWW) [2], [8], [9], food processing waste [12], potato processing starch waste [2], dairy waste [12], [13], brewery waste [12]–[16], pulp and paper mill effluent [2], sulfite mill evaporator condensate [2] and saponification wastewater from propylene oxide plant [17]. It has been also successfully applied for the aerobic digestion of both primary and

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secondary municipal sludge [3], [18]. The basic shaft-type configuration has been upgraded as hybrid bioreactor with addition of tyre-tube beads as bio-carrier media in order to improve the treatment capacity of conventional ASP for treating high organics containing synthetic wastewater [19], anaerobic treated effluent from molasses-based distillery unit [20] and composite wastewater from chrome tannery unit manufacturing wet-blue leather [21]. The experiences in successfully operating the full-scale deep-shaft activated sludge plant subjected to high organic loading have been described [22], [23]. The performance of aeration characteristics, increase in dissolved oxygen concentration and oxygen absorption efficiency in a deep U-tube reactor has been assessed and the results indicated that deep U-tubes offer excellent potential for efficient oxygen transfer systems [24].

The performance of a pilot-scale deep-shaft wastewater treatment plant without inter-stage settlement has been evaluated and the plant was able to fully nitrify the incoming wastewater [25]. A large-scale investigation revealed that deep-shaft activated sludge technology is capable of treating high biochemical oxygen demand (BOD) containing wastewater efficiently [26]. The performance of a full-scale deep-shaft plant treating mixed industrial and domestic wastewater has been successfully monitored at Anglian Water Authority's sewage treatment works at Tilbury with considerable energy savings [27]. The construction, operation and oxygen transfer mode of the deep-shaft aeration for a 'chemical wastewater' treatment plant at Orgamol SA, Rhone valley, Switzerland have been reported with high COD and BOD removal [28]. The operation and performance of the deep-shaft process have been studied in order to determine the rate of intensification of wastewater treatment in relatively compact aeration tank [29]. The success of previous studies of the deep-shaft ASP was based on the principle that increasing the depth of aeration basin enhanced the efficiency. Being motivated by this principle, the present work is conducted for biological treatment of carbonaceous matter in a shaft-type activated sludge reactor. The objective of this work is to evaluate the efficacy of a laboratory-scale shaft-type ASP reactor over the conventional ASP for high-rate wastewater treatment.

II. MATERIALS AND METHODS

A. Experimental Set-up

The shaft-type activated sludge reactor, used for the present study, was developed in the laboratory. The volume of the reactor was approximately 14.5 L and that of secondary clarifier was 5.8 L. Five numbers of pipes were arranged inside the reactor up to the base. Out of them, four pipes were used for aeration purpose and one for feed supply. A conical shaped hopper with a sludge waste outlet was provided at the bottom of the reactor. An inclined tube as intermediate settler was also attached to the reactor to facilitate better sludge separation. There were three outlet ports in this intermediate settler to collect sample from various depths. The secondary

clarifier was equipped with a trough to collect the effluent under overflow mode. Feeding and recirculation to the reactor were done by means of two peristaltic pumps. The schematic diagram of the shaft-type activated sludge reactor used in the study is shown in Fig. 1.

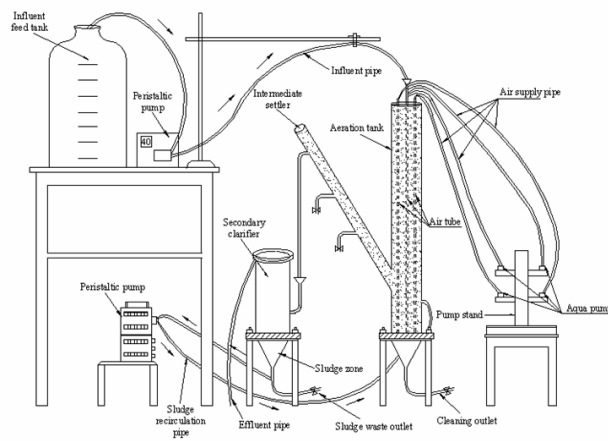


Fig. 1 Schematic diagram of the experimental set-up

B. Synthetic Wastewater

Stock synthetic wastewater was prepared in tap water by mixing different chemicals containing organic carbon, macro- and micro-nutrients. The composition of stock synthetic wastewater was adjusted in such a way that COD becomes approximately about 10000 mg-L⁻¹. The working synthetic wastewater containing varying COD concentrations was prepared by diluting appropriate volume of stock synthetic wastewater with tap water. The detailed composition of the stock synthetic wastewater is presented in Table I.

TABLE I
COMPOSITION OF SYNTHETIC WASTEWATER

Compounds	Concentration (mg-L ⁻¹)
C ₆ H ₁₂ O ₆ (Dextrose)	10000
NH ₄ NO ₃	2857
KH ₂ PO ₄	894
MgSO ₄ · 7H ₂ O	45
FeCl ₃ · 6H ₂ O	0.5
CaCl ₂	55
K ₂ HPO ₄	43.5
Na ₂ HPO ₄ · 7H ₂ O	66.8
NH ₄ Cl	3.4

C. Acclimation of Biomass and Reactor Start-up

Domestic wastewater was collected from a nearby drain and placed in the reactor with addition of tap water. The whole reactor content was kept under aerobic condition by supplying adequate air from the four numbers of aqua pumps, each of airflow capacity of 1.33 L·min⁻¹. The reactor was fed with working synthetic wastewater as mentioned above under batch mode. Various parameters like pH, mixed liquor suspended solids (MLSS), sludge volume index (SVI), COD and

dissolved oxygen (DO) concentration of the reactor were monitored regularly. The acclimated stage of biomass was considered when uniform removal of COD was observed under similar operating conditions. Batch study was performed with this acclimated biomass with varying initial COD concentrations. Subsequently, continuous study was conducted with working synthetic wastewater under different hydraulic retention time (HRT).

D. Batch Study

In the batch study, working synthetic wastewater was added to the reactor step by step to vary the COD concentration in the range of 1000–3500 mg·L⁻¹. The batch study was performed for a period of 9 h for every initial COD concentration and samples were collected initially and at a batch interval of 3 h for analysis. During this batch mode of operation, adequate aeration was ensured by six numbers of aqua pumps. Parameters like pH, MLSS, SVI, COD and DO concentration of the reactor content were analyzed. The quasi-steady state data from batch study were used to determine the kinetic coefficients of carbon oxidation.

E. Continuous Study

The reactor was operated in continuous mode under varying HRT to evaluate the performance exclusively for carbon oxidation. A COD concentration of around 1000 mg·L⁻¹ was fed under different HRTs of 3, 5 and 8 h for the continuous study. The sludge was recirculated from the secondary clarifier by means of a peristaltic pump to maintain a constant biomass of around 3200 mg·L⁻¹ and the recirculation continued with a ratio of 1:2. Various parameters, including influent and effluent COD, effluent suspended solids (SS) and MLSS of the reactor at the initial and final stage were measured. All the parameters were measured at quasi-steady state condition. The DO concentration in the reactor always maintained more than 2 mg·L⁻¹ during the continuous operation to ensure requirement of DO for carbon oxidation.

F. Analytical Methods

All the parameters were analyzed according to the procedures described in the Standard Methods [30]. The analysis of each parameter was done in triplicate using triple distilled water.

III. RESULTS AND DISCUSSION

A. Evaluation of Kinetic Coefficients

Basic equations that describe the interaction between the growth of microorganisms and utilization of the growth-limiting substrate in activated sludge processes are based on widely used Monod model. In a batch-growth culture system, the resulting expression for the rate of substrate utilization (r_{su}) as per Monod model can be written as follows [31]:

$$\frac{X_0 T}{S_0 - S} = \left(\frac{K_s}{k} \right) \left(\frac{1}{S} \right) + \left(\frac{1}{k} \right) \quad (1)$$

In (1), S_0 , S , T and X_0 represent the initial soluble COD concentration (mg·L⁻¹), final soluble COD concentration (mg·L⁻¹), batch period (h) and MLSS concentration at the start of batch period (mg·L⁻¹) respectively. K_s and k denote half-velocity constant or substrate concentration at one-half the maximum specific growth rate (mg COD·L⁻¹) and the maximum rate of substrate utilization per unit mass of microorganisms (h⁻¹) respectively. The values of kinetic coefficients i.e. K_s and k can be estimated from the slope and intercept of (1). Similarly, considering endogenous decay, the resulting expression for the net rate of growth of biomass (r'_g) in a batch-growth culture system as per Monod model can be written as follows [31]:

$$\frac{r'_g}{X_0} = \frac{X_1 - X_0}{X_0 T} = Y \frac{(S_0 - S)}{T X_0} - k_d \quad (2)$$

In (2), X_1 is MLSS concentration at the end of batch period (mg·L⁻¹) and the other parameters are mentioned earlier. Y and k_d denote the maximum yield coefficient (mg SS/mg COD) and endogenous decay coefficient (h⁻¹) respectively. The values of kinetic coefficients i.e. Y and k_d can be estimated from the slope and intercept of (2).

The batch study data under purely suspended growth condition i.e. initial and final biomass concentrations as well as initial and final soluble COD concentrations were arranged in accordance with (1) and (2) in order to evaluate the kinetic coefficients related to substrate removal and microbial growth. The values of the kinetics coefficients i.e., K_s , k , Y and k_d were obtained as 2040.2 mg COD·L⁻¹, 0.105 h⁻¹, 0.878 mg SS/mg COD and 0.0025 h⁻¹ respectively. Table II summarizes some of the kinetic coefficients obtained for ASP treating different types of wastewaters. The values of the kinetic coefficients, obtained from previous studies can be gathered from different sources [32], [33]. The values of K_s and k are significantly different from that of the conventional ASP [31] and they showed high rate of removal in the present reactor. It has been further supported by the high value of yield coefficient (Y) compared to other high rate ASP systems. Only the endogenous decay coefficient (k_d) perfectly tallied with the conventional one. The obtained value of Y is slightly higher than that reported for conventional ASP treating municipal wastewaters. It clearly revealed that the shaft configuration of ASP can have a significant effect on the kinetic coefficients apart from the type of substrate and bacterial consortium.

TABLE II
KINETIC COEFFICIENTS FOR ASP TREATING DIFFERENT WASTEWATERS

Substrate	Y (mg·mg ⁻¹)	k_d (d ⁻¹)	k (d ⁻¹)	K_s (mg·L ⁻¹)	Reference
MWW	0.40-0.80	0.025-0.075	2.0-10.0	15-70	[31]
MWW	0.46-0.60	0.05-0.16	9.3-16.9	250-3720	[34]
MWW	0.35-0.45	0.05-0.10	6.0-8.0	25-100	[35]
MWW	0.50-0.70	0.10-0.20	5.7-16.0	5-30	[36]
Glucose	0.50-0.62	0.025-0.48	11.9-37.0	11-181	[37]
Synthetic	0.390	0.170	49.23	345	[38]
Synthetic	0.590	0.139	19.93	115	[39]
Synthetic	0.878	0.060	2.52	2040.2	This study

B. Reactor Performance

The COD removal was observed to be rapid followed by fast growth of biomass. The reactor performance was found to be relatively stable with respect to MLSS concentration in the reactor. The continuous study revealed that the reactor performance was more stable under comparatively higher HRT of 8 h. The inclined tube attached to the main reactor facilitated intermediate settling of the flocculated biomass, thereby improving the effluent quality. A 50% recirculation of return sludge could maintain a uniform biomass concentration in the reactor. The influent and effluent COD concentration profile of the reactor is shown in Fig. 2. It is evident from Fig. 2 that the adopted HRTs exerted significant effect on the reactor performance in terms of COD removal. About 50% COD removal was attained corresponding to HRT of 3 h whereas about 80% COD removal efficiency was achieved for HRT of 8 h.

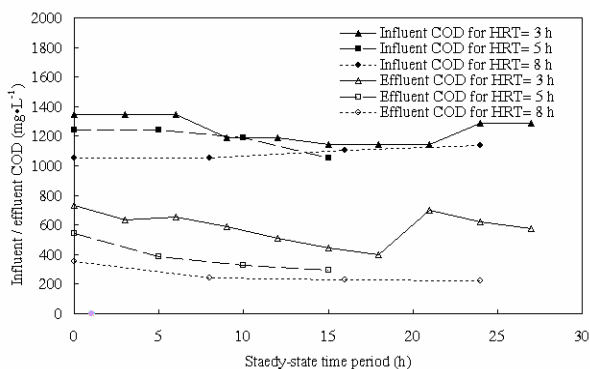


Fig. 2 Influent and effluent COD profile during continuous study

The reactor performance is also expressed in terms of design parameters like COD loading rate and food-to-microorganism (F/M) ratio (COD basis). Therefore, the COD removal efficiency is plotted against COD loading rate and F/M ratio in Fig. 3 and 4, respectively. The performance profile indicated that maximum about 80% COD removal was attained at a COD loading rate of $3.4 \text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$. The F/M ratio corresponding to 80% COD removal was observed to be about $1.0 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$. The reactor could withstand appreciable COD loading rate and F/M ratio of $10.8 \text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ and $2.20 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ respectively depicting a COD removal efficiency of about 46%. The COD loading rate yielding about 80% removal efficiency is observed to be $3.4 \text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$, which is more than three times of that for extended aeration system [31]. This fact confirmed the high efficiency of the present reactor under moderate loading condition. The reactor can also be loaded with F/M ratio of about $1.0 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$, which is 2.5 times of the maximum F/M ratio for extended aeration system [31]. Therefore, the reactor is expected to treat moderately strong wastewater (near $1000 \text{ mg}\cdot\text{L}^{-1}$) satisfactorily within a reasonable time period of 8 h.

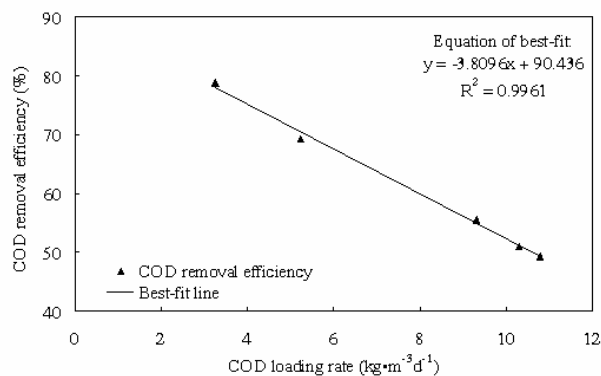


Fig. 3 Effect of COD loading rate on COD removal efficiency

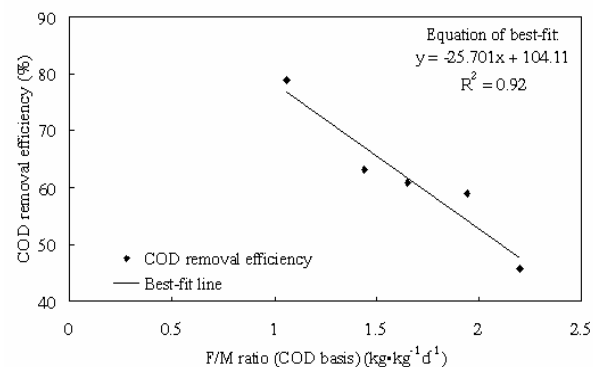


Fig. 4 Effect of F/M ratio (COD basis) on COD removal efficiency

C. Sludge Settleability

The batch operation showed that the biomass achieved a good settleability within a short period. Many authors recognized SVI as the best parameter for characterizing the sludge settling properties. In practice, SVI can vary from 30 to $400 \text{ ml}\cdot\text{g}^{-1}$ for conventional ASP [40], [41]. However, it usually does not exceed the value of $150 \text{ ml}\cdot\text{g}^{-1}$ which is an indicator of good settling properties of the sludge. Sludge having SVI over $150 \text{ ml}\cdot\text{g}^{-1}$ is often classified as bulking sludge [42]. The same authors also pointed out that quickly settling sludge (SVI below $70 \text{ ml}\cdot\text{g}^{-1}$) resulted in turbid effluent due to weakly structured and small flocs [42]. The measured values of SVI during batch study showed little variation and are in the range from 40.5 to $61.3 \text{ ml}\cdot\text{g}^{-1}$. The SVI values obtained in the experiment are rather low, compared to the results reported by other authors. SVI gradually decreased along with the growth of biomass in the reactor as shown in Fig. 5. This indicates the dependence of SVI on MLSS in the reactor. SVI values of different magnitudes for activated sludge in four aeration tanks working in a row were observed and the values were $517 \text{ ml}\cdot\text{g}^{-1}$ in the first tank, $300 \text{ ml}\cdot\text{g}^{-1}$ in the second, $91 \text{ ml}\cdot\text{g}^{-1}$ in the third, and $51 \text{ ml}\cdot\text{g}^{-1}$ in the fourth [43].

A proper SVI value, especially below $100 \text{ ml}\cdot\text{g}^{-1}$, is of great importance in the activated sludge process. Better organic compounds removal by well-settleable sludge (of low SVI) has been demonstrated [44]. However, in the conventional secondary clarifier, activated sludge with low SVI contributed the suspended solids being carried over to the effluent [45]. This tendency has not been observed during the continuous study in the reactor. SVI values of activated sludge as low as $30\text{--}60 \text{ ml}\cdot\text{g}^{-1}$ in a bench-scale sequencing batch reactor was obtained without any turbid effluent [46]. The sludge bulking or filamentous bulking problem was not observed during both batch as well continuous studies since sufficient DO concentration ($>2 \text{ mg}\cdot\text{L}^{-1}$) was present in the reactor. The sludge from the shaft-type reactor was highly flocculated in nature showing a good settleability. Moreover, the modification of the shaft-type reactor with addition of a slant tube as an intermediate settler facilitated good sludge separation.

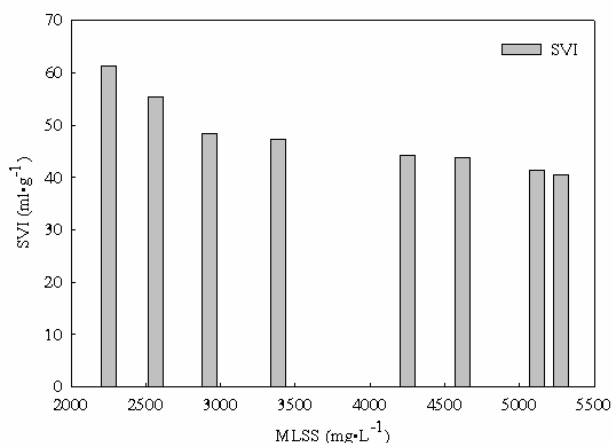


Fig. 5 Change in SVI of sludge as a function of MLSS in the reactor during batch study

IV. CONCLUSION

The present study for biological treatment of carbonaceous wastewater in the shaft-type activated sludge reactor suggests that the treatment capacity of activated sludge process can be improved by shaft configuration. The shaft-type reactor can be used as a viable tool for high-rate wastewater treatment. There was no scarcity of DO under moderate loading condition in the shaft-type reactor. The modification of a shaft-type reactor with addition of a slant tube as an intermediate settler facilitates good sludge separation. The sludge from the shaft-type reactor was highly flocculated in nature showing a good settleability. The reactor is expected to treat moderately strong wastewater within a reasonable time period of 8 h. The shaft-type reactor of present configuration can achieve a maximum COD removal efficiency of about 80% for a COD loading rate of $3.4 \text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ and F/M ratio of $1.0 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ under a HRT

of 8 h. The reactor was also found to handle a COD loading rate and F/M ratio of $10.8 \text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ and $2.20 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ respectively showing a COD removal efficiency of about 46%. This system in its present configuration may be recommended for high-rate treatment of moderately strong wastewater.

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