Journal of Environmental Sciences (China), Vol. 3, No. 1, pp. 11–28, 1991 ISSN 1001-0742

Petroleum waste biodegradation with porous biomass support system (PBSS) on rotating biological contactor

Tran T. Francis[1] and Chowdhury A. K. M. M.[1]

(Received October 22, 1990)

Abstract—A laboratory scale study was conducted to assess the feasibility of the new coupling of rotating biological contactor (RBC) plus porous biomass support system (PBSS) using polyurethane foam as porous support media to biodegrade petroleum refinery wastewater. Polyurethane foam was attached on disks of two four-stage laboratory scale cascade connected RBC units.

The two RBC units were operated simultaneously at different but constant, flowrates giving hydraulic loading rates of 0.01, 0.02, 0.03, 0.04 $m^3/m^2/d$ in two runs keeping the same rotational speed 10 r/min throughout. Organic loading was a less controllable factor in this study.

For all of the hydraulic loadings, it was found that the removal efficiency of total chemical oxygen demand (TCOD) and oil were above 80 percent. Ammonia nitrogen and phenol removal were above 90 and 80 percent respectively. The maximum biomass concentration within polyurethane foam was about 30 g/m^2 in the first stage for 0.03 $m^3/m^2/d$ hydraulic loading.

The results show that this new technology can be applied effectively for practical purposes with moderate hydraulic loading rates.

Keywords: petroleum waste; biodegradation; rotating biological contactor.

INTRODUCTION

Petroleum waste is a priority pollutants in the natural environment. Petroleum refineries generate a considerable amount of wastewater and release a complex set of oxygen-demanding materials. The stabilization of these complex wastes is a great problem. At the present time, many of the refinery effluents are treated using costly physico-chemical processes (Gloyna, 1963).

Effective applications of biological treatment technology is likely to reduce markedly the cost of treating refinery wastewaters. A number of successful full-scale biological systems specially designed for the removal of petroleum hydrocarbons have caught the attention of the

---

[1] Asian Institute of Technology, Bangkok, Thailand.

concerned industries, regulatory authorities and engineers. Interest so far has focused on the application of suspended growth biological systems such as the activated sludge process but there is a great potential for the application of attached growth (fixed-film) biological systems.

Perhaps the most commonly used aerobic fixed-film process in wastewater treatment is the trickling filter but the rotating biological contractor (RBC) has recently gained more attention. This system has a good potential because of the large amount of biomass present and low operating food to microorganism (F/M) ratio which permits the system to withstand hydraulic and organic surges more effectively (Antonie, 1976). It is also an attractive engineering alternative for low cost wastewater treatment because of its short process detention time, excellent shock and toxic loading capabilities, simple precess control and low energy requirements (Wu, 1982). Conventional rotating biological contactor (RBC) have been proven suitable for treatment of municipal and other medium strength wastewaters. However, RBC will not be efficient for treating high-strength wastes. Recently, the use of polyurethane foam was found to be an emerging technology for biological wastewater treatment by the E.P.A. (Environmental Protection Agency) of USA. It acts as a porous biomass support medium (Lewis, 1984).

In this study an approach was made to design a RBC with polyurethane foam as a porous biomass support system (PBSS) on each side of the component disks to biodegrade refinery wastewater. This porous support could offer an enlarged area of contact and adherence for bacterial action. This study intended to investigate the efficiency of the treatment (removal of organics, ammonia nitrogen and suspended solids) for various hydraulic loadings (hydraulic retention time) of the wastewater and to determine the effect of hydraulic loadings on the removal efficiency of those parameters.

EXPERIMENTAL INVESTIGATION

Two bench scale identical 4-stage conventional RBC were used for this study to operate at two different hydraulic retention time in the same time. As shown in Fig. 1 each reactor consists of four similar stages and each stage was cascade connected by a perforated plate which was sandwiched by two baffles. Polyurethane foam of 1 cm thickness was attached on both sides of each disk. These disks were connected to a single stainless steel shaft which was pivoted at both ends and rotated by a variable speed motor using a reducing gear technique. The unit was made of acrylic with the specifications given in Table 1.

The wastewater was collected from a refinery in Bangkok, Thailand (Bangchak refinery). The wastewater was collected from the effluent of American Petroleum Institute (API) separator, which remove most of the sludge and floating oil through settling and slimming. The wastewater was found widely varied in character, because of different operating conditions, shut-off of separator and repairing in the operation processes in the refinery. Waste water was collected once a week and stored in a dark container in order to minimize the effect of sunlight, at normal temperature. Due to degradation and volatilization almost all parameters measured, got reduced in their value with time. The characteristics of wastewater found during the experiment are given in Table 2.

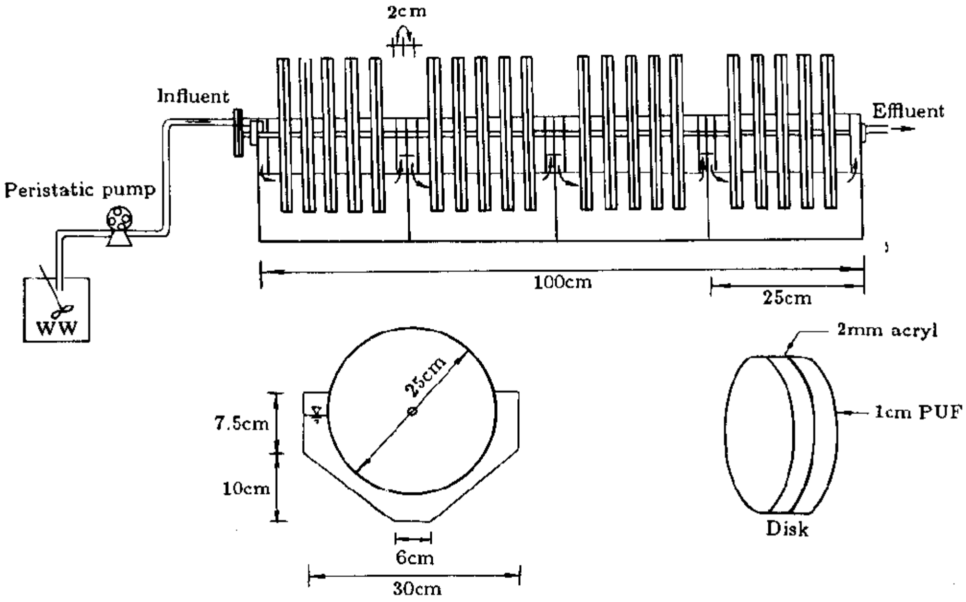

Fig. 1 The schematic of RBC unit

Table 1 Summary of the dimensions of the RBC experimental units

Specifications	Value
Number of stages	4
Number of disk/stage	5
Disk diameter, cm	25
Disk thickness, mm	2
Foam thickness (on each side of disk), cm	1
Disk spacing, cm	1.67
Total surface area/stage, m^2	0.49
Water volume/stage, L	6.2
Submergence, %	42.5
Rotational speed, r/min	10
Porosity of PUF, %	85

During start-up of the experiment, a seeding with mixed liquor of activated sludge process unit of the same refinery was used to speed up the microorganism growth in the reactors. The units were filled with a mixture of refinery and Asian Institute of Technology (AIT) domestic wastewater and were continued with flow corresponding to the hydraulic loading for 3 days. After three days thin biofilm was observed on the disks of both units. Then the flow of refinery waste was increased and full flow was started after one week. The steady state condition was achieved after 3 weeks.

Table 2 Characteristics of wastewater

Parameters	Minimum — Maximum
TCOD, mg/L	234.45 — 925.20
Oil, mg/L	26.47 — 124.73
Phenol, mg/L	6.42 — 88.03
Ammonia nitrogen, mg/L	3.28 — 51.65
Suspended solids, mg/L	63.87 — 110.06
pH	7.31 — 7.76
TCOD/BOD ratio	2.6

The following hydraulic loadings were varied with two loading in each run, i.e., 0.01 and 0.02 $m^3/m^2/d$ in the first run and 0.03 and 0.04$m^3/m^2/d$ in the second run, where hydraulic loading represents the volume of wastewater per unit surface area of disk per unit time. Here both sides of all the disks of the RBC unit were considered for calculation of total surface area. These hydraulic loadings corresponds to hydraulic retention times of 30.37, 5.18, 10.12 and 7.59 hrs respectively. Changes in hydraulic loading were conducted by varying the flowrate of the wastewater. In this case organic loading was a less controllable factor. Throughout the experiment the rotational speed of the units was fixed at 10 r/min and room temperature varied between 23°C to 32°C in ambient condition.

The parameters measured were total chemical oxygen demand (TCOD). Soluble chemical oxygen demand (SCOD), ammonia nitrogen(NH_3-N), nitrite nitrogen (NO_2^-), nitrate nitrogen (NO_3^-), oil and grease, phenol, suspended solid (SS), pH and dissolved oxygen(DO). All the analytical methods used were conducted according to standard methods (Apha, 1985) and are listed in Table 3. All of these parameters were measured in the influent to the RBC unit and at the end of each stage at steady state. For all of these measurements, sampling frequency was twice a week.

Biomass of biofilm and biomass within polyurethane foam was determined. The biofilm biomass was determined by scraping biomass from a known surface (4 cm × 4 cm) of the polyurethane foam at the periphery of the disk (first and last disk of each stage). But for the entrapped biomass within polyurethane foam, the foam of that area (4 cm × 4 cm) was cut down to squeeze and washed to get total biomass entrapped within polyurethane foam. Then from the biomass weight and the cutting surface area, the average total biomass in terms of dry weight per unit surface area of disk of each stage was calculated.

Table 3 Analytical methods used for different parameters

Parameters	Analytical methods used
TCOD	Dichromate reflux method (Apha, 1985)
SCOD	Ditto
NH_3-N	Titrimetric & Nesslerization method (Apha, 1985)
NO_2^-	Cadmium reduction method (Apha, 1985)
NO_3^-	Ditto
Oil & Grease	Soxhlet extraction method (Apha, 1985)
Phenol	Direct photometric method (Apha, 1985)
SS	Standard method (Apha, 1985)
pH	Digital pH meter
DO	Membrane electrode DO analyzer

RESULTS AND DISCUSSION

COD removal

During the first run, the steady state was obtained within three weeks and for the second run it took two weeks to attain steady state (Fig. 2), which is shorter compared to about 7 weeks or more (Knowlton, 1977). Polyurethane foam which act as porous support media plays an important role in rapid start-up (Rozzi, 1989).

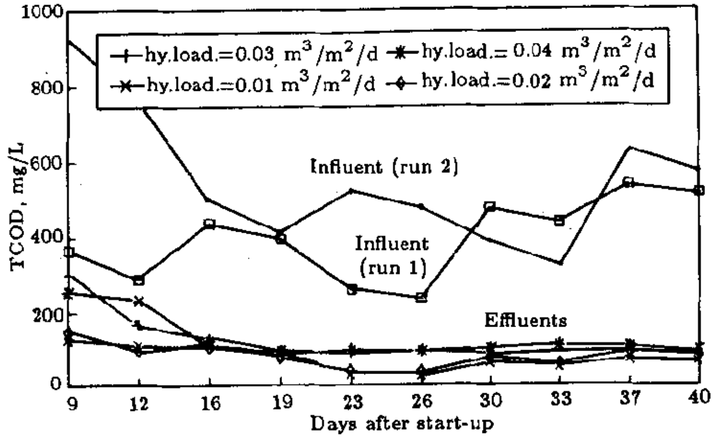

Fig. 2 Performance of RBC treating refinery wastewater for COD removal

Fig. 3 shows that most of the organics removed in first stage for all of the hydraulic loadings than that removed in the later stage two to four, that is because of inflow to later stages contains organic matter in particulate form which is difficult to oxidize. The first stage shows higher performance because it receives the high organic loading, which is attributed to the high growth of carbonaceous bacteria in first stage. The main process undergoes here is carbonaceous substrate removal and endogenous respiration, resulting in thick biofilm forming and low dissolved oxygen concentration. Also, biomass in polyurethane foam in this stage was dense, because of high intake loading and easy diffusion of substrate through the porous structure. Also increase of flow rates for the first and the second run at a constant influent concentration resulted in an increase of both effluent COD concentration and rate of COD reduction with a decrease in the percentage and mg/L COD reduction. The most plausible explanation is that the organic removal is mass transfer limited because organics in the layer of water immediately adjacent to the slime layer is depleted rapidly. At low flow rates the concentration gradient penetrates into the bulk liquid film thus reducing the magnitude of the concentration gradient, as mass transfer is directly proportional to the concentration gradient. At high flow rates the concentration gradient limited to a thin liquid film adjacent to the slime layer and further increase of liquid feed rate gave no effect. This is obvious in the second run for 0.03 $m^3/m^2/d$ and 0.04 $m^3/m^2/d$ hydraulic loading. This phenomenon could be due to oxygen transfer limiting condition in 0.04 $m^3/m^2/d$ hydraulic loading.

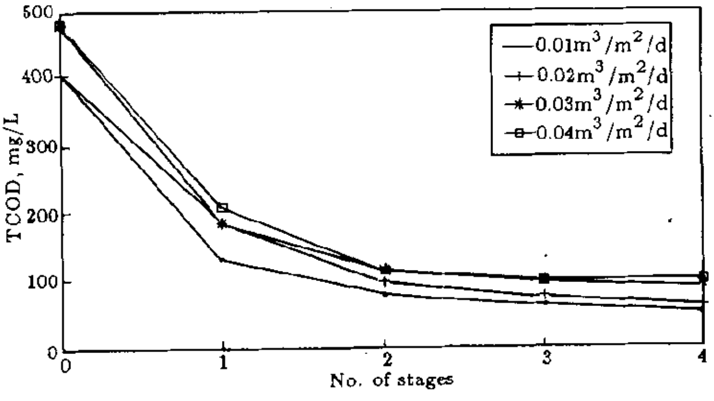

Fig. 3 COD (av.) removal at different hydraulic loadings at steady state

Table 4 Performance of RBC at different loading conditions

No. of run	1		2	
Hydraulic loading, $m^3/m^2/d$	0.01	0.02	0.03	0.04
Organic loading, $g/m^2/d$	2.3—5.3	4.7—10.7	9.5—18.8	12.7—25.1
	(1.2—2.5)	(2.4—5.1)	(5.1—10.1)	(6.8—13.4)
Av.organic removal, $g/m^2/d$	3.6	6.9	11.8	15.5
	(1.5)	(2.8)	(5.4)	(7.3)
Av. percent removal	87.5	84.9	81.5	80.2
	(76)	(72.3)	(70.3)	(71.9)

Note: All data are from average values at steady state. The data in parentheses are for SCOD and others for TCOD.

Organic loading was a less controllable factor in this study. Total organic loading in terms of TCOD and SCOD used in this investigation is given in Table 4. For both TCOD and SCOD loading, it shows that with increasing organic loadings, organic removal rates increase but percentage of organic removal decreases. Also the organic removal is almost proportional to the organic loading. It supports that the removal of COD can be described by a substrate limiting phenomenon (mass transport) as well as oxygen limiting reaction. Pano and Middle Brooks (1983) also found that organic removal was relating to substrate limiting condition.

It is also found that SCOD removal efficiency was less than that for TCOD removal for all these cases. This is due to the low soluble matters like oil and grease suspended matter which contributed more in TCOD.

Oil and grease removal

Oil removal in RBC takes place effectively because of the property of biomass of adsorption and retention of oil. Rotation brings the oil droplets in contact with air inflating the surface area of the oil droplets. This helps the uptake of molecular oxygen which is essential during the first step of break-down of hydrocarbons by oxygenase enzymes (Davies, 1968).

Fig. 4 shows that for lower loadings, the oil removal was high from the beginning of the start-up: this could be due to the soaking effect of polyurethane foam, which has effectively been used for oil soaking (Cooper, 1984). It is found that oil concentration varies widely throughout the experimental study, revealing good absorbance of shock loading by this system. Antonie (1976) reported that the rotating contactor process appears to handle oil and grease as high as 375 ml/L with no deleterious effects.

Oil removal tendency per stage follows the same pattern as that for COD reduction, because oil has direct contribution to COD values as shown in Fig. 5. Consequently conclusions drawn for COD, can directly be applied to behavior of oil. It is found that for a constant hydraulic loading, high oil concentrations are more readily used than at low concentrations, although in both cases, approximately the same effluent concentration is produced. This phenomenon was

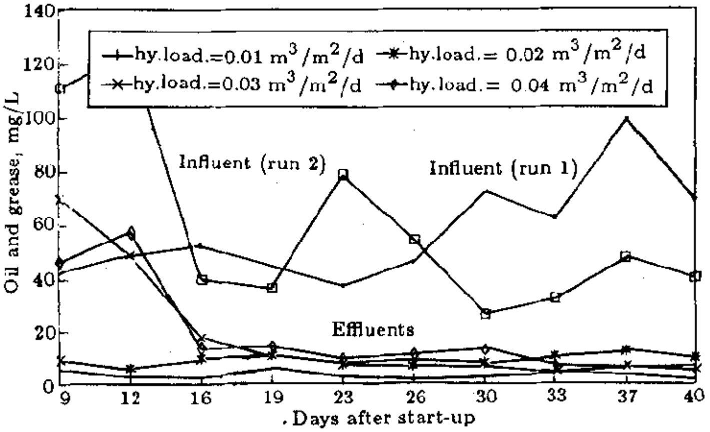

Fig. 4 Performance of RBC treating refinery wastewater for oil removal

also supported by Antonie (1976). But with increase of hydraulic loading the overall effluent concentration is increased.

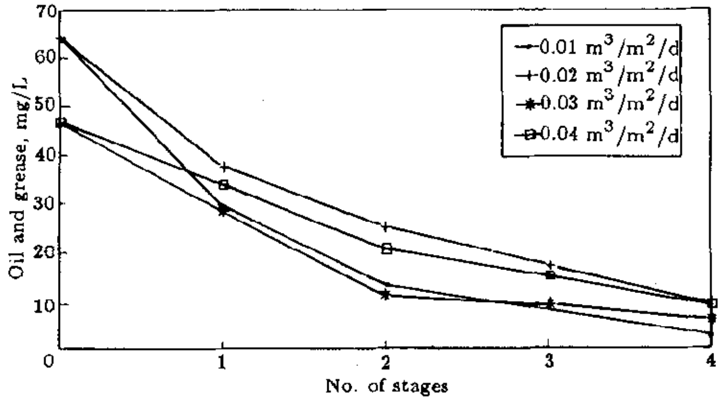

Fig. 5 Oil (av.) removal at different hydraulic loadings at steady state

The temperature is one of the main factor affecting oil removal. Although the temperature of the fresh refinery wastewater is high (40—45°C) which is detrimental to biological activity. In this case, as water was stored in room temperature, normal bacterial activity took place and this has been observed by Sono and Futaka(1966). The microbial oxidation is most rapid when the temperature ranges from 15°C to 35°C. The pH range between 6.5 to 8.0 is imperative to be maintained during the experiment, in all stages for all the runs (Eckenfelder, 1966). In this case pH range was within that limit and during the whole experiment the temperature was within the range(15—35°C). Average oil removal was above 80% which is almost same as that obtained by other researchers using conventional RBC (Antonie, 1976; Chou, 1981).

Phenol removal

Phenol is one of the major soluble organic compounds in refinery wastewater. Fig. 6 shows that phenol concentration varies from minimum 6.42 mg/L to maximum 88.03 mg/L, which is within the normal range of 10 to 100 mg/L of refinery wastewate (Rosfjord, 1976).

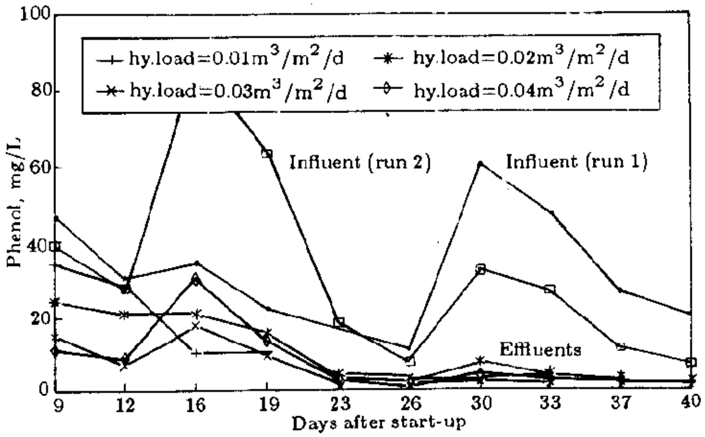

Fig. 6 Performance of RBC treating refinery wastewater for phenol removal

The content of phenol directly relates to COD. Almost all the factors controlling COD removal per stage in different loading also affect phenol removal. In addition, the aeration by rotation and contact of biofilm-water to air may strips volatile organics from the water adding to the removal efficiency, although it contributes little in overall removal efficiency (Bracewell, 1980).

Temperature plays a significant role in the performance of biological degradation of phenol. Higher temperature enhance phenol removal. Antonie and Davis (1976) found that the range from 32°C to 38°C is optimum for biological degradation. During the whole period of these experiments, the temperature varied within the range 26°C to 34°C. So it was edging the optimum temperature range for phenol removal.

In stage one, maximum removal (about 50%) took place because of high phenol concentration, which helps for the growth of a stabile phenol adapted culture on the media. Percentage of phenol removal (87.6%, 88.3%, 90.8% and 93.6%) was inversely proportional to hydraulic loading of 0.04, 0.03, 0.02 and 0.01 $m^3/m^2/d$, respectively. The removal efficiency in this case is less than that obtained by Antonie (1976) and Hamoda *et al.* (1976), because of high influent concentration. For influent levels of 10 mg/L and less, more than 95% removal was achieved at

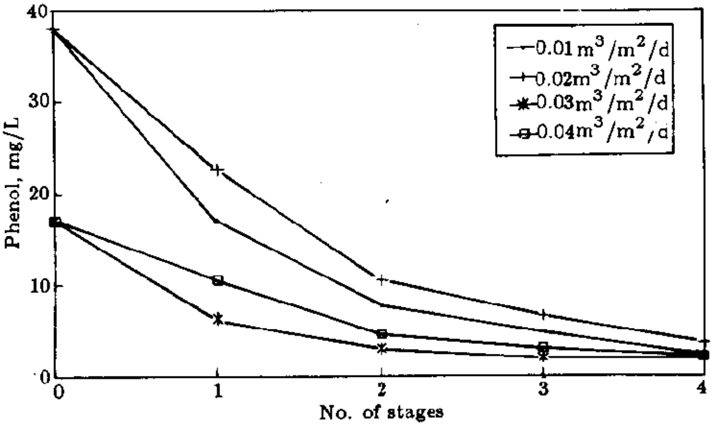

Fig. 7 Phenol (av.) removal at different hydraulic loadings at steady state

hydraulic loading generally under 0.08m^3/m^2/d and over 80% removal for loadings up to 0.12 m^3/m^2/d (Antonie, 1976). Choung *et al.* (1968) found that there was no evidence of substrate inhibition for phenol concentrations less than 100 mg/L. They got more than 95% removal efficiency for phenol concentration 50 to 314.5 mg/L, using synthetic phenolic wastewater for RBC.

Removal of ammonia nitrogen

In the first run, for both hydraulic loading (0.01 and 0.02 m^3/m^2/d) effluent ammonia nitrogen concentration were almost zero at steady state. The effluent concentration varied from 0 to 4.19 mg/L for all of the loadings, giving overall 99.6, 96.9, 91.6 and 88.9 percent removal from lowest to highest loadings respectively (Fig. 8).

In stage one of Fig. 8, maximum removal took place at lowest loading 0.01 m^3/m^2/d. This is due to cell synthesis and nitrification, because DO and pH was favorable for nitrification and also the bacterial film was sparsely dark brown (Clark, 1978) which shows that nitrifying bacteria were present. Besides nitrification the removal can also be related to assimilation (Hitdlebaugh, 1980). Contrarily to domestic waste, refinery wastewater contains much less organic nitrogen, therefore the culture consumes a greater portion of the ammonia nitrogen for cell synthesis. Antonie (1976) found that this amounted to 50% of the ammonia present for NH_3-N concentration 15–22 mg/L.

With increasing hydraulic loading values, the percentage of removal in stage one decreases. From DO values (Fig. 9) it is found that nitrification did not take place in case of 0.03 m^3/m^2/d and 0.04 m^3/m^2/d, as the minimum DO limit for nitrification is from 1 to 2 mg/L that with increase of loading nitrification took place in later stages. It can be supported by observed color in stages, because for 0.02 and 0.03 m^3/m^2/d loading in last two stages (3rd

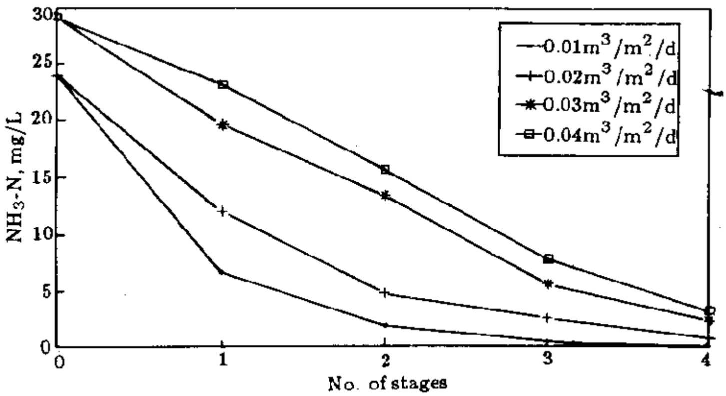

Fig. 8 NH_3-N (av.) removal at different hydraulic loadings at steady state

and 4th) greenish color was observed but at 0.04 $m^3/m^2/d$ only last stage (4th) was greenish, i.e., with increase of hydraulic loading the nitrifying bacteria moves backward. This shows that the concentration of BOD controls nitrification phenomenon. Antonie (1974) found that nitrification begins in the RBC process when the wastewater BOD concentration approaches 30 mg/L. At this concentration, nitrifying organisms can compete with the more rapidly growing carbon oxidizing organisms and establish themselves in the process. Nitrification then proceeds rapidly until, at a BOD concentration of approximately 10 mg/L, the nitrification is complete.

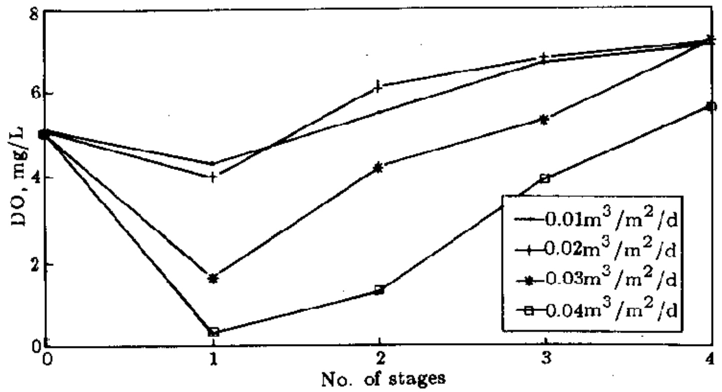

Fig. 9 DO profile per stage for different hydraulic loadings at steady state

It is clear from Fig. 10 and Fig. 11 that nitrification took place in stages two to four. It is found that complete nitrification (by conversion of NO_2-N to NO_3-N) was not achieved in both cases. But in case of 0.03 $m^3/m^2/d$ there was a sign of decreasing NO_2-N in stage four. Again from these figures, it can be concluded that NH_3-N was removed not only due to nitrification but also due to bacterial assimilation, by summing-up NO_2-N and NO_3-N and comparing with initial NH_3-N concentration.

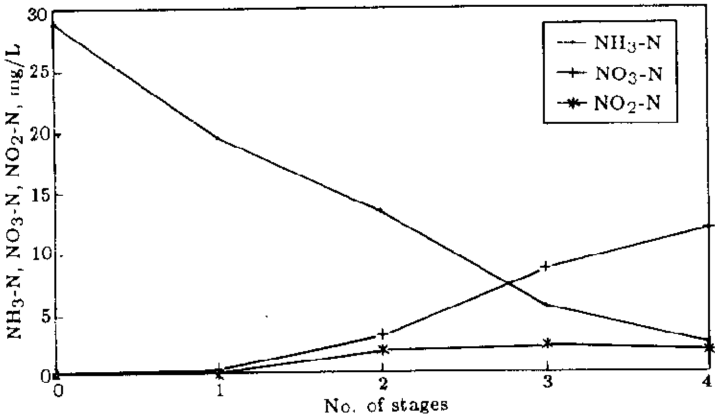

Fig. 10 Nitrification at different stages for 0.03 $m^3/m^2/d$ loading

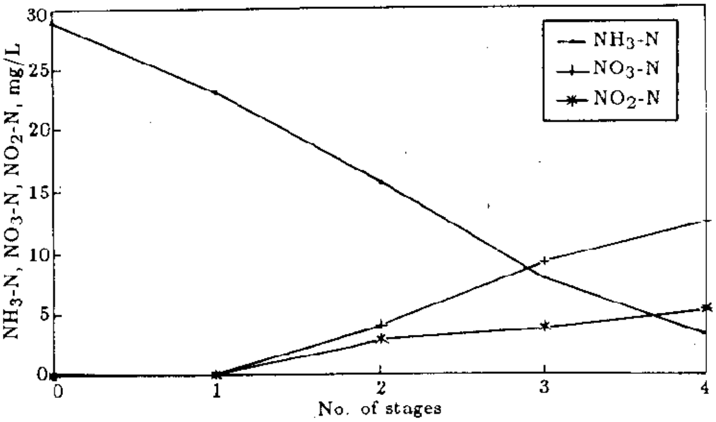

Fig. 11 Nitrification at different stages for 0.04 $m^3/m^2/d$ loading

For 0.03 and 0.04 $m^3/m^2/d$, an attempt was made to do nitrogen balance and to find amount of denitrification assuming amount of biomass (TVS) formed is half of TCOD removed and amount of N_2 consumed for assimilation is 10% of TVS formed. Using average values it is found that for 0.03 and 0.04 $m^3/m^2/d$, TCOD removed 23.31 g/d and 30.34 g/d, respectively. So, amount of biomass (TVS) formed was 11.57 g/d and 15.17 g/d and amount of N_2 consumed for assimilation was 1.157 g/d and 1.517 g/d for two loadings respectively. For refinery wastewater, organic nitrogen concentration was assumed zero. Total average influent N_2 (NH_3-N, NO_3-N, NO_2-N) was 1.72 g/d and 2.30 g/d for 0.03 and 0.04 loadings. This amount should be equal to the sum of N_2 used for nitrification, assimilation, denitrification and amount of N_2 remaining in the form of NH_3-N. The amount of nitrification (taking average values of NO_3-N and NO_2-N at the effluent) was 0.81 g/d and 1.37 g/d and remaining amount of NH_3-N at the effluent was 0.144 g/d and 0.251 g/d for 0.03 and 0.04 $m^3/m^2/d$ respectively. In both cases it is found that sum of N_2 used for assimilation, nitrification and remaining N_2 was 2.111 g/d and 3.163 g/d which is greater than influent total N_2 1.72 g/d and 2.30 g/d respectively. From which it can be concluded that amount of denitrification took place was very low for both loadings.

The other factors which affect ammonia removal are pH, DO and temperature. In this case except for the first stage for highest loading rate, DO level was above the critical limit (1—2 mg/L).. In all stages pH was in the range (7—8.5) as reported by Hitdlebaugh and Miller (1980). The nitrification rate is more sensitive to temperature than the rates for organic removal. Temperature in this experiment was within the range (23–35°C) being the optimum range set by many researchers.

The removal efficiencies obtained was almost above 90% for all of the loadings which is superior to those obtained by Hamoda and Al-Haddad (1987). They got above 80% for 0.03, 0.06, 0.12 $m^3/m^2/d$ using aerobic submerged fixed film treatment for refinery waste.

Suspended solids and fixed film biomass

Fig. 12 shows the average removal of suspended solids per stage for different hydraulic loadings at steady state. From this figure, it is clear that the first stage concentration increases with increase of loadings. Effluent concentration increases significantly in case of highest hydraulic loading. For the first three loadings, concentration of SS of stage three and stage four remian in the victinity of 20 mg/L with removal percentage of 81.6, 80.4, 78.2 and 69 respectively for increasing hydraulic loadings or decreasing detention time.

Biofilm growth on disks varied widely in thickness, color and nature, from stage to stage at various hydraulic loadings. The biofilm in the first stage at hydraulic loadings 0.01 to 0.03 $m^3/m^2/d$ and in the first and second stages at hydraulic loading of 0.04 $m^3/m^2/d$, was obviously thicker than that remaining in other stages. It was also more spongious. The higher organic loading and removal rates in these stages could be the cause of the thickness of the biofilm. Conversely, inferior organic loading corresponds to thinner biofilm in the later stages (Fig. 13 and Fig. 14).

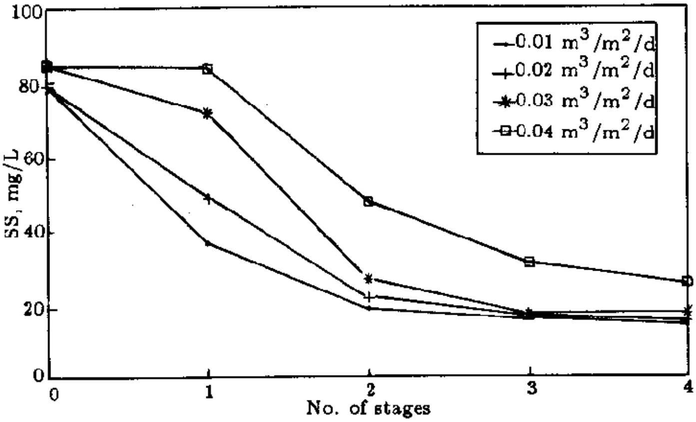

Fig. 12 SS (av.) removal at different hydraulic loadings at steady state

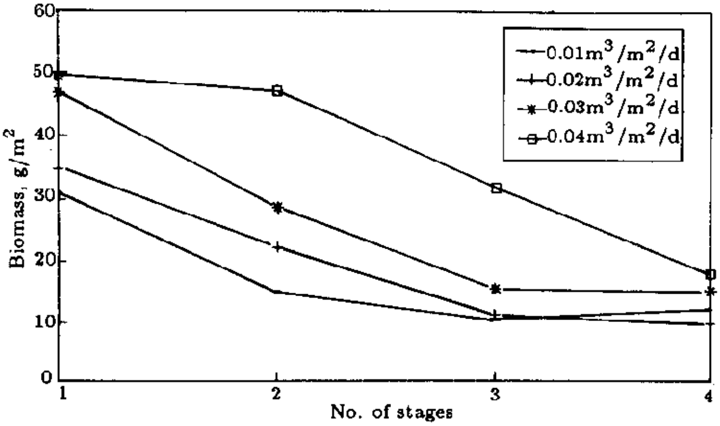

Fig. 13 Biomass product in biofilm per stage at different hydraulic loadings

In the first stage of both loadings (0.03 and 0.04 $m^3/m^2/d$), the sulfur bacteria *Beggiatoa* was found in the first and second disks associated to their white milky appearance. Low DO and sulphide presence in refinery wastewaters enhanced the growth of this type of bacteria, responsible for a fall in the organic removal.

Fig. 15 and Fig. 16 show the variation of DBI (Disk Biomass Index) per stage for different hydraulic loadings for both biofilm and biomass in polyurethane foam respectively. DBI is defined as the ratio of total volatile solids to total solids of the disk biomass $[(gTVS/m^2)/(gTS/m^2)]$. It represents the amount of active biomass on the disk. A declining tendency of DBI is observed in both figures. The DBI values decreased from stage one to stage four, but it increased

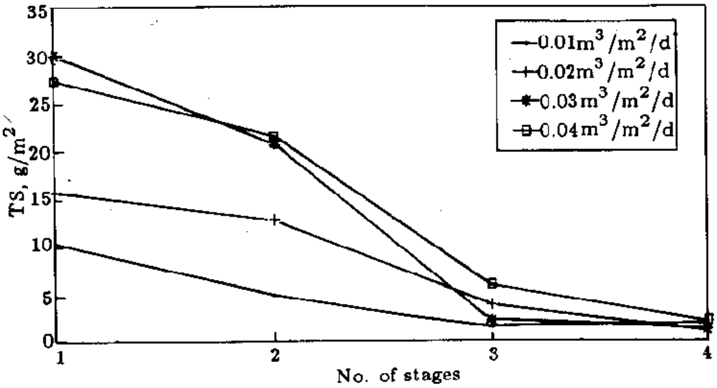

Fig. 14 Biomass in polyurethane foam of disk in stages of RBC for different hydraulic loadings

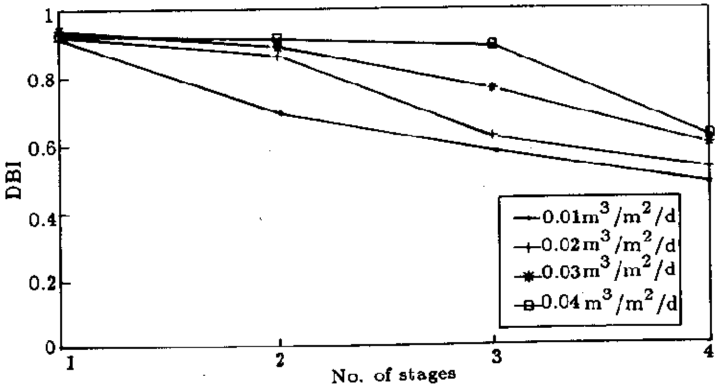

Fig. 15 DBI (biofilm) per stage at different hydraulic loadings at steady state

stage wise when hydraulic loading was increased (Fig. 15). It is due to the availability of organic substrate in the first stage and lower availability of organics in the following stages. The higher and more stable values of DBI in the first stage for all loadings are due to the existence of common type of carbonaceous oxidizing bacteria. Whereas in the later stages, DBI varies widely because of the presence of a large diversified organisms on the biofilm. This can be caused by the decrease in organic loading in the later stages, where higher trophic organisms and nitrifying bacteria begin to take over the carbonaceous oxidizing bacteria. But DBI values of polyurethane foam (Fig. 16) biomass did not show that a clear tendency of decreasing DBI with stages for a constant hydraulic loading. Also with increase of loadings, the DBI did

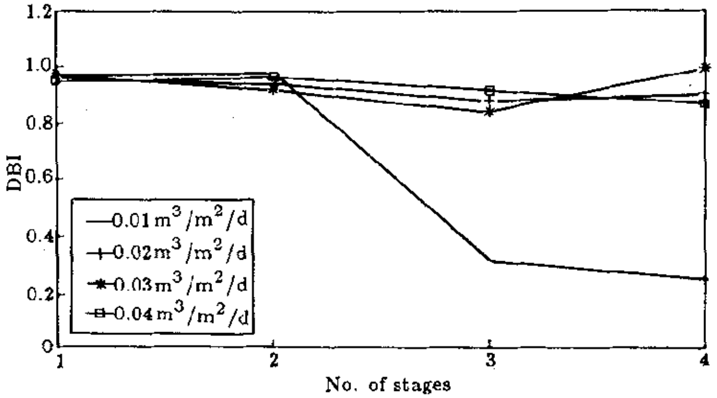

Fig. 16 DBI (polyurethane foam) per stage at different hydraulic loadings at steady state

not vary from stage to stage as it used to occur in case of biomass of on conventional RBC's biofilm. This might be due to the presence of common type of bacteria in all stages within the polyurethane foam.

CONCLUSIONS

On the basis of results of laboratory scale experimental investigation, following conclusions can be drawn:

1. The new coupling of RBC plus polyurethane foam used as PBSS showed good organic (TCOD) removal efficiency for all hydraulic loadings. Although average removal efficiencies were 87.5, 84.9 and 80.2% for 0.01 to $0.04m^3/m^2/d$ hydraulic loadings, which show a decreasing trend with decrease of detention time, overall removal efficiency was better than conventional RBC's without polyurethane foam.

2. Oil removal performance was good (above 80%) although it decreases with increase of hydraulic loading or decrease of detention time. Soaking effect of polyurethane foam enhanced the removal in later stages.

3. The new system also performed well in terms of phenol removal. Removal efficiency for phenol did not vary significantly (85—95%) for such a high concentration of phenol used in this experiment than the conventional one.

4. Ammonia nitrogen removal rate was almost above 90% for all of the loadings. It is almost similar to that obtained in case of conventional RBC for domestic waste. Less amount of organic nitrogen in refinery wastewater facilitates the increase of ammonia nitrogen removal. The removal is almost complete with only traces of ammonia left. Dissolved oxygen and pH

conditions throughout the stages facilitate nitrification.

5. For SS removal, the performance was similar to conventional RBC. At highest loading, removal efficiency decreases rapidly from 80% to 70% showing less tolerance at higher loadings.

6. Biomass investigation on biofilm and within the polyurethane foam showed that higher biomass fixation on biofilm was observed than conventional RBC for similar organic loadings. Also, biomass behavior on polyurethane foam according to organic loadings followed the same tendency. The simultaneous use of biofilm and polyurethane foam clearly proves higher biomass accumulation on disks, thanks to the porous biomass support system which takes part actively in organic removal.

The new coupling of RBC plus polyurethane foam performed well. Polyurethane foam did not show any side effect. Polyurethane foam is cheap and no deterioration was observed in polyurethane foam after 3 months continuous operation. Considering all of these factors, it can be concluded that this system can be used economically for refinery waste treatment.

REFERENCES

Antonie, R. L., Water and Sewage Works, 1974, 121 (1): 44, Nov.; 121 (2): 54, Dec.

Antonie, R. L., Fixed biolgical surfaces-wastewater treatment: RBC, CRC Press Inc. Cleveland, Ohio, 1976: 94; 113

Apha, Standard methods for examination of water and wastewater, Washington, D. C.: American Public Health Association, 16th ed., 1985

Bracewell, W. L., Jenkins, D. and Cameron, W., Proc. 1st National Symposium/ Workshop on RBC Technology (Eds. by Smith, E., Miller, R. D. and Wu, Y. C.), USA: Pennsylvania, 1980: 733

Chou, C. C. and Hynek, R. J , Proc. 35th Ind. Waste conf., Purdue Univ., Ann Arbor Science Publishers Inc., Woburn, Mass, 1981: 855

Choung, Y. K., Bae, B. H. and Ahn, K. H., Water pollution control in Asia (Eds. by T. Panswad, C. Polprasert and K. Yamamoto), Pergamon Press, 1988: 685

Clark, J. A., Moseng, E. M. and Asano, T., JWPCF, 1978, 50 (5): 896

Cooper, P. E., Walker, I., Crabtree, H. E. and Aldred, R. P., Conf. on the process engineering aspects of immobilized cell systems, England: Manchester Pergamon Press Ltd., 1986

Davies, J. B., Petroleum Microbiology, Amsterdam, London, N. Y.: Elsevier Publishing Co., 1967: 379

Davies, J. A. and Hughes, D. E., The Biochemistry and Microbiology of Crude Oil Degradation, Field Studies, 1968, 2: 139

Eckenfelder, W. W., Industrial Water Pollution Control, N. Y.: McGraw Hill Book Co., 1966: 178

Gloyna, E. F. and Malina, J. F., Water and Sewage Works, Ref. No. P. 1963: R273

Hamoda, M. F. *et al.*, J. biotechnol., 1987, 5:279

Hamoda, M. F. and Al-Haddad, A. A., A Pilot Study of Aerobic Submerged Fixed-Film Treatment of Petroleum Refinery Wastewaters, 1987: 283

Hitdlebaugh, J. A. and Miller, R. D., Proc. 1st National Symposium/Workshop on RBC Technology (Eds. by Smith, E., Miller, R. D. and Wu, Y. C.), Pennsylvania, 1980: 31

Knowlton, H. E., Oil and Gas Journal, 1977, 75 (40): 86

Lewis, J. A., Black, G. M., Mavituna, F. and Wilkinson, A., Conf. on the process engg aspects of immobilized cell systems, England: Manchester Pergamon Press Ltd., 1986: 291

Pano, A. and Middle Brooks, J. E., JWPCF, 1983, 55 (7): 956

Rosfjord, R. E, *et al.*, Water and Sewage Works, 1976, 123 (3): 97

Rozzi, A., Passino, R. and Limoni, M., Process Biochemistry, 1989, 24 (2): 68

Sono, K. and Futaka, M., 3rd Int. Conf. on Water Poll. Res., Munich, W. Germany, 1966

Wu, Y. and Smith, E., Journal of the Environmental Engineering Division, ASCE, 1982, 108 (3): 578