SEWAGE TREATMENT IN A ROTATING BIOLOGICAL CONTACTOR (RBC) SYSTEM

A. TAWFIK[1,*], H. TEMMINK[2], G. ZEEMAN[2] and B. KLAPWIJK[2]
[1]*National Research Center, Water Pollution Control Dept. El-Behoos St., Dokki, P. Box 12622, Giza, Egypt;* [2]*Wageningen University Research centre, Agrotechnology and Food Sciences Department, Sub-department of Environmental Technology, P.O. Box 8129, 6700EV, Wageningen, The Netherlands*
*(*author for correspondence, e-mails: tawfik8@hotmail.com, tawfik8@yahoo.com; Fax: +2-02-3370931)*

(Received 17 May 2005; accepted 11 March 2006)

Abstract. The treatment of domestic wastewater at a temperature of 12–24 °C was investigated in an RBC system. The RBC consists of a two stage system connected in series. The system was operated at different organic loading rates (OLR's) and hydraulic retntion times (HRT's) in order to optimize the RBC performance. The overall removal efficiencies for chemical oxygen demand (COD_{total}, $COD_{suspended}$ and $COD_{colloidal}$) significantly decreased when decreasing the total HRT from 10 to 2.5 h and increasing the OLR from 11 to 47 g COD/m^2.d. However, the effluent quality of $COD_{soluble}$ remained unaffected.

Most of the COD was removed in the 1st stage and nitrification took place in the 2nd stage of the two stage system.The overall nitrification efficiency was 49% at total OLR of 11 gCOD/m^2.d. At total HRT's of 10, 5 and 2.5 h, the Escherchia coli (E. coli) concentration was reduced by a value of 1.6, 1.5 and 0.8 $\log_{10}$ respectively.

The sludge volume index (SVI) decreased as the OLR increased. However, the SVI of the excess sludge produced in the RBC under different OLR's was always $<$ 74 ml/gTS, which indicates a good settleability.

The performance of the single versus two stage RBC operated at the same total OLR of 22 g COD/m^2.d and the same HRT of 5.0 h was examined. The results obtained showed that the COD concentration and the E. coli content in the final effluent of a two stage were lower than in the effluent of the single stage RBC. Moreover, the nitrification efficiency in the two stage system was higher comapred to one stage system.

Keywords: sewage, RBC, OLR, SRT, COD, nitrification, E. coli, sludge

1. Introduction

In developing countries, the problem of sanitation increases due to the increase in population density accompanies by an increase in water consumption. The disposal of domestic wastewater without any treatment into the drainage systems is considered a source of pollution threatening the population. Current mainstream technologies for treatment of domestic wastewater, such as activated sludge and tertiary nutrient removal are too costly to provide a satisfactory solution. Rotating

Water, Air, and Soil Pollution (2006) 175: 275–289
DOI: 10.1007/s11270-006-9138-6

Biological Contactor (RBC) system represents an excellent option for sewage treatment (Ayoub and Saikaly, 2004). Because it allows a sufficiently long biomass retention time, compact unit, low energy cost, easy operation, high process stability, less footprint requirement, and high specific removal rate (Tawfik, 2002a). Research conducted in an RBC system was particularly directed for improving its performance. The effect of temperature, disc rotating velocity and different disc support media on the performance of RBC was studied by Rittmann *et al*. (1983); Patrick (1983), and Kinli (1999), while Gilbert *et al*. (1986) investigated energy consumption and savings in an RBC system. RBC's have been tested in both single stage system and in sequential stage configuration for biological oxygen demand (BOD_5) removal and nitrification from municipal wastewater (Huang, 1986).

Akunna and Jefferies (2000) compared the performance of a Rotating Biological Contactor (RBC) and Sequencing Batch Reactor (SBR) for sewage treatment at the same operating conditions. Both units produced the same effluent quality of BOD_5 (20 mg/l) and SS of 30 mg/l. The efficiency of a trickling filter, a submerged filter and a RBC system for treatment of UASB reactor effluent was compared by Van Buuren, (1991). He found that at an HRT of 3.3 h, the trickling filter and the submerged filter removed 50% of COD_{total} while, the RBC removed 70%. Moreover, at much shorter HRT of 0.24 h the RBC still achieved 40–80% COD_{total} removal. He therefore, concluded that RBC's are more effective in removing organic matter than trickling filter and submerged filter. This was attributed to a better contact between the wastewater and the biofilm and to the higher oxygen concentrations prevailing in the RBC. Moreover, he also found much lower surface ammonia removal rates in the two stage trickling filter and in the submerged filter as compared to the two stages RBC under the same operating conditions.

The objectives of the present investigation are to,

1. examine the COD, ammonia and E.coli removal at different OLR's in a two stage RBC system treating domestic wastewater.
2. compare the performance of a two stage with a single stage RBC system operated at the same total loading rate with respect to COD, ammonia and E. coli removal.

2. Materials and Methods

Up-on applying the RBC on full scale, shafts failure problems appeared to represent a serious problem especially when using rotating discs from material with a high specific surface area, and/or high density such as plastic material (Griffin and Findlay, 2000). This study was carried out to overcome the shaft failure problems by using unique polystyrene rotating discs with low density, and light. Moreover, the proposed RBC has another advantage that, it contains in the lower part an immhoff settling tank. The final clarifier therefore is not required. This system was continuously operated for 3.5 years without any problems (Tawfik, 2002a).

2.1. Pilot plant

A schematic of the RBC is shown in Figure 1. The RBC consists of two identical stages connected in series. Each stage had a working volume of 60 l (including immhoff settling tank with 15 l capacity) and was equipped with 10 polystyrene foam discs with a total effective surface area of 6.5 m^2.The discs was rotated at 5.0 rpm. The disc diameter was 0.6 m with a thickness of 0.02 m and they were spaced at 0.02 m distance. The submerged surface was 40%. The discs were mounted on a steel shaft.

2.2. Wastewater characteristics and operational conditions

The sewage used in the experiment was from the village Bennekom, The Netherlands. The sewage is collected in a combined sewer system and is continuously pumped to the experimental hall after screening of fine grit, and debris. Peristaltic pump with a variable flow rate of 10 to 1000 ml/min was used to pump influent wastewater to the reactors.

The mean values of the influent COD_{total}, $COD_{suspended}$, $COD_{colloidal}$ and $COD_{soluble}$ were 508 ± 123, 251 ± 120, 109 ± 64 and 148 ± 35 mg/l respectively. Influent ammonia-nitrogen and total Kjeldahl nitrogen (TKN) were 55 ± 11 and 62 ± 9 mg/l respectively. The pH values remained between 6.7 and 7.1. Average E. coli content in the influent wastewater amounted to $5.9 \times 10^6 \pm 3.9 \times 10^6/100$ ml. The wastewater temperature varied from 12 to 24 °C.

This study describes results of three experimental runs conducted at the following different flow rates:

- 0.29 m^3/d (HRT = 10 h and OLR = 11 g COD/m^2.d) during 4.0 months
- 0.58 m^3/d (HRT = 5 h and OLR = 23 gCOD/m^2.d) during 3.0 months

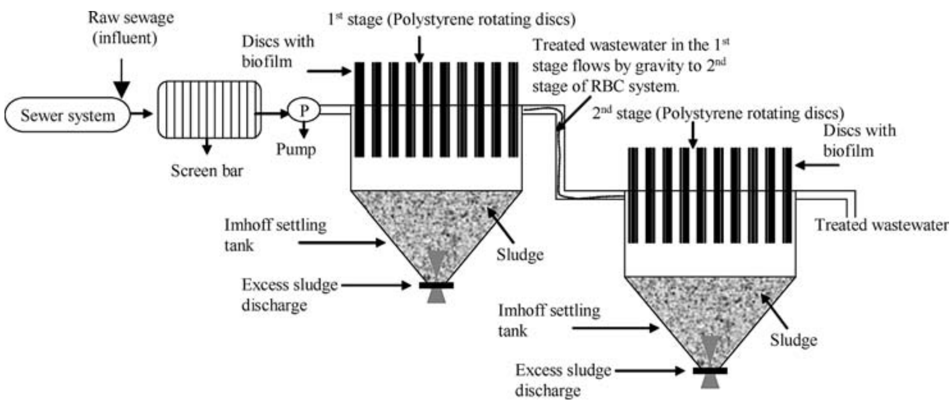

Figure 1. Schematic represantation of the two syages of RBC system treating domestic wastewater

– 1.15 m^3/d (HRT = 2.5 h and OLR = 47 gCOD/m^2.d) during 3.0 months.

Initially, the system was operated for 37 days to achieve a steady state conditions (Tawfik *et al.*, 2002b). An acclimation period of 15 days was allowed between experimental runs to attain steady state conditions. Steady state was presumed to have been established when the daily changes in the effluent COD were within 5% for three successive days.

2.3. SAMPLING AND ANALYTICAL METHODS

48 hrs, composite samples of the influent and the effluents were pumped using a timer controlled peristaltic pumps (200 ml/h) and collected in containers stored in a fridge at 4 °C (APHA, 1998).

Parameters like DO, pH and temperature were daily measured by using DO meter (INOLAB Oxi level 2, E163694), pH meter (INOLAB pH 720 SET). The COD was analysed using the micro-method (closed reflux colorimetric) as described by Jirka and Carter (1975). Raw samples were used for COD_{total}, 4.4 μm folded paper filtered (Schleicher & Schuell 595 1/2) samples for $COD_{filtrate}$ and 0.45 μm membrane filtered (Schleicher & Schuell ME 25) samples for soluble COD ($COD_{soluble}$). The $COD_{suspended}$ and $COD_{colloidal}$ were calculated by the difference between COD_{total} and $COD_{filtered}$, $COD_{filtered}$ and $COD_{soluble}$, respectively. Ammonia, nitrite and nitrate were determined on auto-analyser (SKALAR SA-9000), TKN according to the Dutch Standard Normalized Methods (1969) and E. coli according to the method described by Havelaar and During (1988).

The excess sludge was daily collected from the immhoff settling tank of 1st and 2nd stage of the RBC system in a two storage tank (10 l each) for sludge analysis. Sludge weight at 105 and 550 °C were determined according to APHA (1998). The sludge biomass index (SBI) defined as the ratio of total volatile solids to total solids of the settled sludge in the tank (Loy, 1988).

2.4. CALCULATIONS

For calculating the sludge residence time (SRT), it is assumed that the effluent VSS had the same SRT as the excess sludge. The SRT(d) for RBC system was calculated according to the following equation,

$$SRT = \left(\frac{VxX}{Q_w x X_w + Q x X_e} \right)$$

Where: V, reactor volume (l); X, average sludge concentration in the reactor (mgVSS/l); Q_w, excess sludge flow rate (l/d); X_w, concentration of the excess sludge (mg VSS/l); Q, wastewater flow rate (l/d); X_e, effluent concentration (mgVSS/l).

2.5. Statistical analysis

Statistical analysis at different HRT's has been done according to Snedecor and Cochran (1980). The performance of the system at each HRT was assumed to be independent with different variance.

2.6. Biofilm characteristics and microscopic examination

The attached biofilm concentration in the rotating discs at OLR's of 11, 23 and 47 g COD/m^2.d was monthly measured by taking two samples of the rotating discs. Average biomass concentration in one bio-disc (per disc volume) was estimated to be 0.71, 1.2 and 1.6 kgVS/l respectively.

At OLR of 11 gCOD/m^2.d, the calculated thickness of the biofilm in the 1^{st} and 2^{nd} stage RBC system was 2.4 and 1.7 mm respectively. When the loading rate increased from 23 to 47 gCOD/m^2.d, the average biofilm thickness increased from 2.8 to 3.5 mm.

A small part of the attached biomass was also used for microscopic examination, filamentous bacteria dominated in the 1^{st} stage of two stage RBC, whereas, Protozoan such as *Vorticella, Carchesium, Paramecium candatum and Nematozoans* dominated the 2^{nd} stage of the RBC system at a loading rate of 11 gCOD/m^2.d.

3. Results and Discussion

3.1. Efficiency of a two stage RBC system

The results presented in Table I. show that DO concentrations in the mixed liquor increased from stage 1 to stage 2. The DO concentrations decreased in the 1st stage and 2nd stage unit as the OLR increased. This can be due to the higher organic removal rates (ORR's) as shown in Table I.

Figure 2a, b and c show that the residual values for the various COD fractions (COD_{total}, $COD_{suspended}$ and $COD_{colloidal}$) significantly ($p < 0.01$) increased when

TABLE I

Mean DO,OLR, ORR and SRT applied to the RBC system

Parameters	DO (mgO_2/l)		OLR gCOD/m^2.d)		ORR*(gCOD/m^2.d)		SRT (d)	
Run no.	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage
1	1.3	2.3	21.3	7.8	13.5	4	3	10
2	1	1.9	46.7	20	26.5	9.9	2	7
3	0.8	1.5	93.6	54	40	15.3	1	2.8

ORR*(Organic removal rate)

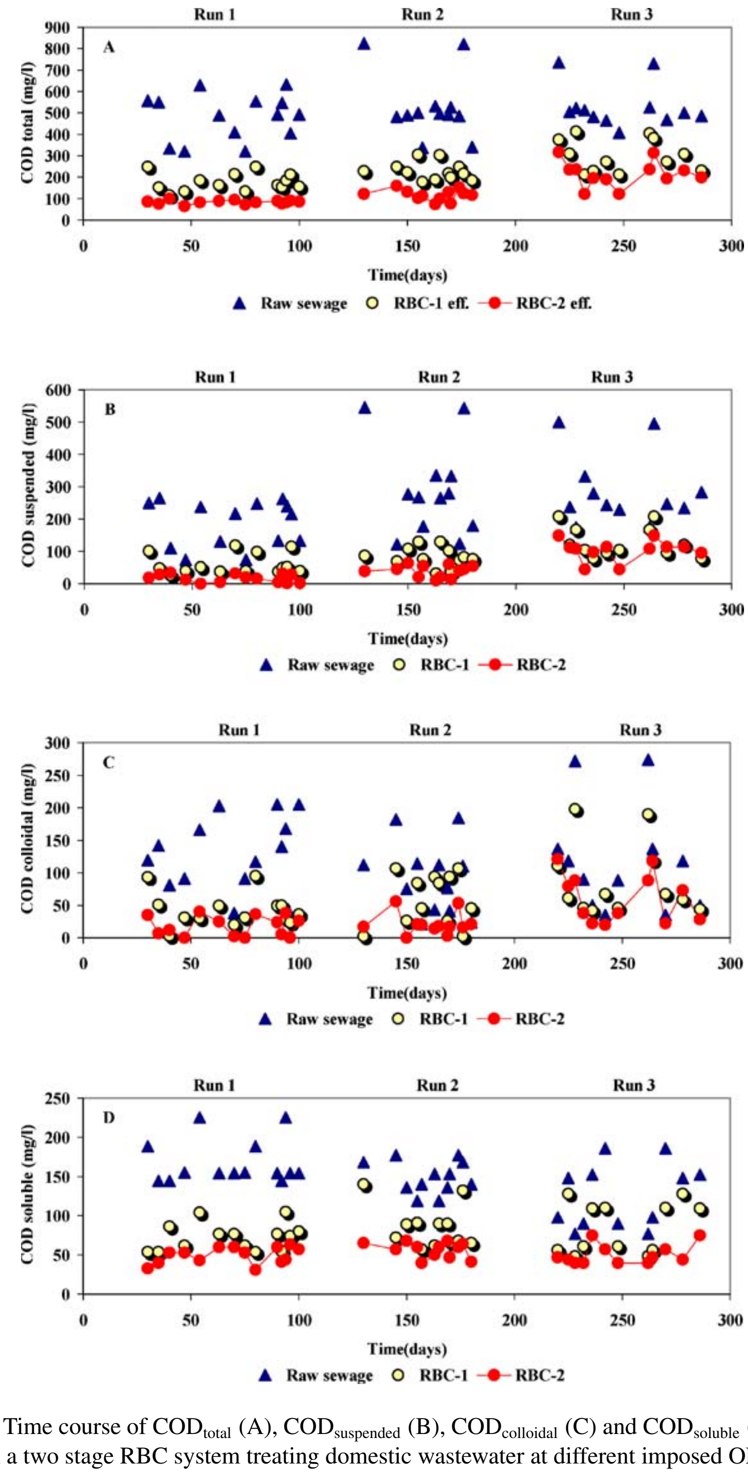

Figure 2. Time course of COD_{total} (A), $COD_{suspended}$ (B), $COD_{colloidal}$ (C) and $COD_{soluble}$ (D) concentrations in a two stage RBC system treating domestic wastewater at different imposed OLR's.

decreasing the total HRT from 10 to 2.5 h and increasing the total OLR from 11 to 47 g COD/m^2.d. However, the effluent quality of $COD_{soluble}$ remained unaffected when increasing the OLR from 11 to 47 gCOD/m^2.d as shown in Figure 2d. This indicates that, in term of $COD_{soluble}$, the system is still under loaded under these conditions.

The results in Figure 2b and c show that the major part of COD particulates ($COD_{suspended}$ and $COD_{colloidal}$) were eliminated in the 1st stage of two stage system especially at OLR of 11 gCOD/m^2.d. Little additional removal was occured in the 2nd stage.

Table II shows that a small amount of ammonia was eliminated in the 1st stage of two stage RBC system at different imposed OLR's. This obviously can be attributed to the low DO concentration and short SRT applied to the 1st stage of the RBC system (Table I). The nitrification mainly proceeded in the 2nd stage of two stage system especialy at lower loading rate (Table II) and higher DO concentration (Table I). However, the nitrification in the 2nd stage RBC system remains insignificant at higher OLR's and lower DO concentrations, i.e. the nitrate concentration amounted to only 1.5 mg/l in both situations. Hanaki, *et al.* (1990a,b) revealed that the inhibitory effect of organic loading on nitrifiers was enhanced by low DO conditions.

In a conventional RBC designed for COD removal and nitrification by Gonenc and Harremoes (1985) the nitrogen balance between the influent and effluent indicated that 8% of influent nitrogen did not appear in the effluent. Table II gives the nitrogen loss across the two stage RBC system.

The results presented in Figure 3 show that the residual count of E.coli significantly ($p > 0.01$) increased when decreasing the HRT from 5 to 2.5 h. However, further removal of E.coli doesn't significantly occur at increasing the HRT to 10 h.

There was a decrease in sludge volume index (SVI) as the loading rate increased while the excess sludge produced and sludge yield coefficient was increased (Table III). This can be due to shorter sludge residence time at high organic loading rate. The sludge biomass index (SBI) of the produced sludge in the two stage RBC modules exceeded the value of 0.6 for all applied organic loading rates. This means that the sludge in the RBC—settling tank system was not sufficiently stabilizied and require further treatment prior to disposal.

3.2. Comparison of the performance of a single and a two stage RBC

The performance of a single stage with a two stage RBC system was compared at the same operating conditions for COD, ammonia and E.coli removal. The results obtained for a single and a two stage RBC system operated at the same HRT of 5.0 h and the same OLR of 22 g COD/m^2.d are presented in Table IV. The results clearly show that the difference values of COD_{total}, $COD_{suspended}$ $COD_{colloidal}$ and $COD_{soluble}$ in the final effluent of a two and single stage are respectively 59, 21, 19 and 16

TABLE II

Mean nitrogen species in a two stage RBC system treating domestic wastewater at different imposed OLR's. Standard deviations are presented in brackets

Parameters			Nitrogen species (mg/l)				Nitrification rate		
Samples	HRT (h)	OLR ($gCOD/m^2.d$)	NH_4^+-N	NO_2-N	NO_3-N	TKN	Nitrogen loss	gNH_4-$N/m^2.d$	gNO_3-$N/m^2.d$
Run 1.									
Sewage			53 (11)	0	0	63 (11)	–	–	–
RBC-1 eff.	5	21.3	43 (10)	0.5 (0.3)	0.8 (0.9)	52 (12)	10 (4)	0.4 (0.4)	0.06(0.01)
%R			17 (15)	–	–	12 (4)	17 (8)		
RBC-2 eff.	5	7.8	28 (10)	0.2 (0.1)	7 (7)	38 (11)	7 (11)	0.7 (0.4)	0.3(0.06)
%R			35 (26)	–	–	25 (22)	12 (23)	–	–
Overall removal efficiency (%)			49 (18)			39 (16)	30 (15)	0.6 (0.2)	0.3(0.06)
Run 2.									
Sewage			49 (8)	0	0	58 (5)	–	–	–
RBC-1 eff.	2.5	46.7	45 (6)	0.4 (0.2)	0	49 (5)	7 (4)	0.16(0.13)	0.04(0.01)
%R			7 (5)	–	–	8 (3)	12 (6)	–	–
RBC-2 eff.	2.5	20	40 (6)	0.3 (0.1)	1.5 (0.7)	42 (5)	5 (6)	0.3 (0.06)	0.13(0.02)
%R			13 (3)			13 (11)	10 (11)	–	–
Overall removal efficiency (%)			19 (6)			26 (10)	23 (9)	0.2 (0.07)	0.08(0.01)
Run 3.									
Sewage			66 (2)	0	0	67 (3)	–	–	–
RBC-1 eff.	1.25	93.6	57 (8)	0.4 (0.2)	0	60 (5)	7 (5)	0.4 (0.3)	0.07(0.02)
%R			13 (12)	–	–	7 (5)	10 (8)	–	–
RBC-2 eff.	1.25	54	47 (9)	0.3 (0.2)	1.7 (1.9)	54 (8)	7 (6)	0.4 (0.2)	0.28(0.03)
%R			18 (9)	–	–	8 (17)	11 (9)	–	–
Overall removal efficiency (%)			28 (15)			19 (13)	20 (8)	0.4 (0.2)	0.18(0.05)

TABLE III

The characteristics of the excess sludge in the two stages RBC system at different imposed OLR's. Standard deviations are presented in brackets

Operating conditions		Organic loading rate (OLR)					
		11 $gCOD/m^2.d$		23 $gCOD/m^2.d$		47 $gCOD/m^2.d$	
Parameter	Unit	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage
Sludge volume	ml/l	881(123)	660 (111)	84 (12)	75 (11)	620 (112)	380 (85)
Sludge weight at 105 °C	g/l	15.3 (2.4)	8.95 (2.6)	29.6 (7)	16.2 (4)	26.4 (12)	8.9 (8)
Sludge weight at 550 °C	g/l	12 (3)	7 (2.5)	23.8 (7)	13.7 (3)	25.6 (5)	7.6 (2.3)
Sludge Volume Index (SVI)	ml/Gts	60 (12)	74 (14)	29.6 (4)	35.3 (7)	23.4(4)	42.6 (8)
Sludge production	g/d	56 (6)	15.8 (4)	59.2(15)	19.4 (3)	60.8(13)	21.4 (2)
Sludge Biomass Index (SBI)	gVS/gTS	0.78 (0.2)	0.79 (0.3)	0.8 (0.3)	0.85 (0.4)	0.97 (0.1)	0.85(0.2)
Sludge yield coefficient	gTS/gCOD removed	0.63 (0.1)	0.59 (0.09)	0.68 (0.23)	0.6(0.02)	0.92 (0.04)	0.84 (0.05)
Sludge yield coefficient	gVS/gCOD removed	0.49 (0.2)	0.46 (0.1)	0.55 (0.02)	0.51 (0.3)	0.89 (0.5)	0.72 (0.6)

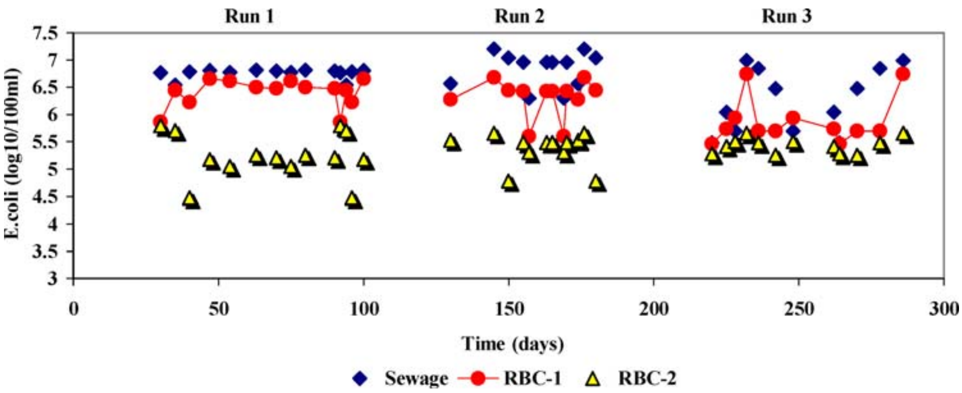

Figure 3. Time course of E. coli concentrations in a two stage RBC system treating domestic wastewater at different imposed OLR's.

mg/l. Moreover, the results obtained in the two stage system revealed a relatively higher overall removal of 20% for ammonia and 31% for TKN compared to 14% and 15% for single stage RBC system, consequently lower ammonia and TKN concentrations in the treated effluent. The high overall COD and ammonia removal in the two stage system compared with a single stage system could be attributed to the staging of the biological conversions in the two stage system. Furthermore, It is clear that the two stage RBC provides lower E.coli concentrations in the final effluent (2.8×10^5/100 ml) as compared to the single stage (2.9×10^6/100 ml) (Table IV). This can be attributed to the abundance of available bacterial adsorption sites on the two stage system. Part of E.coli is removed in the 1st stage as a result of sedimentation i.e, the fraction of E.coli attached on the suspended solids. The free dispersed E.coli are found to be adsorbed or/and predated in the 2nd stage (Tawfik *et al*., 2002b).

4. Discussion

For sustainable sewage treatment in developing countries, the implementation of low cost, simple treatment systems should be encouraged. The results of the present study show RBC system to be an interesting alternative for sewage treatment for regions suffering from a lack of water resources like in the Middle East. The results of these investigations reveal that the two stage RBC system is highly efficient in removing, viz. 86% of COD_{total} is removed at an imposed HRT of 10 hrs and OLR of 11 g COD/m^2.d. However, partially nitrification (49%), and partially E. coli removal (97%) were occurred under these conditions. Boller *et al*. (1987) found that nitrification started at OLR of 15 g COD/m^2.d and was fully developed at OLR of 8.0 g COD m^2/d in an RBC system treating domestic wastewater. However according to Boongorsrang *et al*. (1982) the OLR should be less than 2.5 g COD/m^2·d for

TABLE IV

Comparison between the overall removal efficiency (%R) of a single versus two stage RBC system at the same operational conditions (OLR = 22 gCOD/m^2.d and HRT = 5 h.). Standard deviations are presented in brackets

Sample		Influent	RBC effluents			
Parameter	Unit	Raw wastewater	single stage	%R	two stage	%R
COD_{total}	mg/l	496 (137)	174 (46)	65 (12)	115 (28)	77 (11)
$COD_{suspended}$	mg/l	231 (122)	60 (35)	74 (8)	39 (20)	83 (3)
$COD_{colloidal}$	mg/l	107 (56)	40 (29)	63 (5)	21 (19)	80 (6)
$COD_{soluble}$	mg/l	158 (27)	73 (18)	54 (3)	57 (10)	64 (4)
Ammonia	mg/l	50 (9.9)	43 (9.9)	14 (4)	40 (6)	20 (6)
Nitrate	mg/l	0.0	0.0		1.4 (0.6)	
TKN	mg/l	61 (9.7)	52 (12)	15 (4)	42 (5.0)	31 (5)
E.coli	/100 ml	7.1×10^6 (3.6×10^6)	2.9×10^6 (1.3×10^6)	59 (11)	2.8×10^5 (1.3×10^5)	96 (7)

nitrification in an RBC system. In another study, Cheung, (1986) found that the nitrification efficiency of 90% was achieved in an RBC system treating septic tank effluent at higher OLR of 8–10 g BOD_5/m^2.d.

The results presented here show that there is 0.8 to 1.6 $\log_{10}$ reduction in the concentration of E. coli, which is consistent with E. coli removal in an RBC system treating settled domestic wastewater (Sagy and Kott, 1990), however, at longer HRT. Likewise El-Zanfaly and El-Abagy, (1987) found that RBC system treating domestic wastewater achieved 97.82% for total coliform, 99.74% for faecal coliform and 97.93% for faecal streptococci. The residual bacterial densities were high to represent a potential health hazard such as 10^9 for total coliform, 10^6 for faecal coliform and 10^6 MPN-index/100 ml for faecal streptococci compared to our results where residual E. coli in final effluent was 10^5/100 ml. In an RBC system, adsorption is the main E. coli removal mechanism followed by sedimentation (Tawfik *et al.*, 2004).

Sludge yield coefficient in the 1st and 2nd stage RBC system amounted to 0.63 and 0.59 gTS/gCOD removed at total OLR of 11 gCOD/m^2.d and increased to 0.92 and 0.84 gTS/gCOD removed in the 1st and 2nd stage at total OLR of 47 gCOD/m^2.d. This is comparable with the results obtained by Cheung, (1986) who found that 0.6–0.8 kgTSS/Kg BOD_5 removed was achieved for an RBC system treating septic tank effluent. Surampalli and Baumann, (1995) found that the sludge production amounted to 0.6 kg SS/kg SCOD removed in a full-scale RBC system treating domestic wastewater.

For improving the performance of the RBC system for COD, nitrification, and E. coli removal different methods have been proposed (1) supplemental aertation; (2) step feeding; (3) recycling; and (4) introduction of an anaerobic system such as Upflow Anaerobic Sludge Blanket (UASB) reactor prior to the aerobic RBC system. Surampalli and Bauman, (1997) investigated the effect of supplemental aeration on the performance of full scale RBC treating municipal wastewater. Two four stage trains were investigated under various organic loading conditions with one as a control. Their results show that the use of supplemental air not only improves the COD removal but also significantly enhances the nitrification efficiency of the system.

The effect of step-feed on the performance of RBCs' was studied by Janczukowicz and Klimiuk (1992) where the HLR and OLR were maintained constant while varying the step-feed ratio. They found that higher COD removals and better DO values in the different stages were obtained with a step feed system. Better results were obtained with step feed ratios of 67/33 (applied to the 1st and 2nd stages, respectively) than with ratios of 33/33/33 (applied to the 1st, 2nd and 3rd stages respectively). Ayoub and Saikaly, (2004) investigated the effect of variable HLR's, OLR's, and influent substrate concentrations applied to a three-stage RBC system operating in a step-feed mode. The study concluded that variation in the Hydraulic loading rate (HLR) had insignificant effects on the overall COD and BOD_5 removal but was more effective on ammonia removal. They also found that at low OLR

(COD = 1200 mg/l), the step-feed system was more efficient in terms of ammonia removal; however, no differences were observed in COD and BOD_5 removals. At high OLR's (>1200 mg/l) the step-feed system showed higher efficiencies in the removal of ammonia and COD and higher stage DO concentrations were attained.

The effect of recirculation on treatment efficiencies in RBC's was studied by Guarino *et al*. (1977) where increased BOD_5 and ammonia removals were obtained upon the introduction of recirculation to RBC system located in Philadelphia full-scale treatment plants. Klees and Silverstein, (1992) also reported improved removal efficiencies in COD, BOD_5 and NH_4–N with the introduction of recirculation. Efficiencies were found to increase with increased recirculation ratios. The recent study, investigated by Tawfik *et al.*, (2002c) showed that recycle of the 3rd stage effluent to the 1st stage of the RBC system reduced the residual of E. coli in the final effluent from 2.0×10^3 to 9.8×10^2/100 ml. Moreover, the recirculation of nitrified effluent from the 3rd stage to the 1st stage increased ammonia removal in the stage 1 from 23 to 43%. This can be attributed to the supply of nitrifiers from 3rd stage to the 1st one.

The treatment scheme consisting of an anaerobic pre-treatment step in which a large proportion of the organic matter and suspended solids are removed, generally seem favorable for nitrification and E. coli removal in an RBC system as a post-treatment compared to the situation for treatment of domestic wastewater (Tawfik *et al.*, 2003).

5. Conclusions

1. Increasing the organic loading rate applied to the two stages RBC from 11 to 47 gCOD/m^2.d treating domestic wastewater negatively affected the overall removal efficiency of the treatment process. At an OLR of 11 g COD/m^2.d, the two stage system provided an average residual value of 84 mg/l for COD_{total}, 28 mg/l for ammonia and 2.5 times; 10^5/100 ml for E.coli which is significantly lower than that at OLR's of 23 and 47 gCOD/m^2.d. Considering these results, it is recommended to apply a two stage system for treatment of domestic wastewater at OLR of 11 gCOD/m^2.d and HRT of 10 h.
2. As the loading rate increased, the sludge volume index (SVI) decreased while the excess sludge production and sludge yield coefficient was increased. The sludge biomass index (SBI) of the produced sludge in the two stage RBC modules exceeded the value of 0.6 for all applied organic loading rates. This means that the sludge in the RBC settling tank system was not sufficiently stabilizied and require further treatment prior to disposal.
3. Comparison of the performance of a single stage versus a two stage RBC, under conditions of the same total organic loading rate of 22 gCOD/m^2.d reveal a clear improvement in the two stage system.

Acknowledgement

The first author would like to express his gratitude to EU for financial support of this research. The first author would like to thank R.E. Roersma, B. Willemsen, and S. Hobma for technical support.

References

Akunna, J.C., & Jefferies, C. (2000). Performance of family size sequencing batch reactor and rotating biological contactor units treating sewage at various operating conditions. *Water Science and Technology*, *41*(1), 97–104.

APHA (1998). *Standard Methods for the Examination of Water and Wastewater* (20th ed). Washington, D.C: American Public Health Association.

Ayoub, G.M., & Saikaly, P. (2004). The combined effect of step – feed and recycling on RBC performance. *Water Research*, *38*, 3009–3016.

Boller, M., Eugster, I., Weber, A., & Gujer, W. (1987). Nitrifikation in nachgeschalteten rotierenden tauchkorpern. EAWAG-report.

Boongorsrang, A., Suga, K., & Maeda, Y. (1982). Nitrification of wastewaters containing carbon and inorganic nitrogen by rotating disc contactor. *Journal of Fermentation Technology*, *60*, 357–362.

Cheung, P.S. (1986). The performance of the rotating disc system under the tropical conditions in Taiwan. *Water Science and Technology 18*, 177–183.

Dutch Standard Normalized Methods (1969). The Netherlands Normalisation Institute, Delft, The Netherlands.

El-zanfaly, H., & El-abagy, M. (1987). Removal of bacterial indices of pollution during sewage treatment via rotating biological contactor. *Applied Microbiology and Biotechnology*, 25, 585–589.

Gilbert, W.G., Wheeler, J.F., & MacGregor, A. (1986). Energy usage of rotating biological contactor facilities. *Journal Water Pollution Control Federation*, *58*, 47–51.

Gonenc, I.E., & Harremoes, P. (1985). Nitrification in rotating disc systems: Criteria for transition from oxygen to ammonia rate limitation. *Water Research*, *19*, 1119–1127.

Griffin, P., & Findlay, G.E. (2000). Process and engineering improvements to rotating biological contactor design. *Water Science and Technology*, *41*(1), 137–144.

Guarino, C.F., Marrazzo, W.J., & Nelson, M.D. (1977). Philadelphia develops surfact. Paper presented at 50th annual WPCF conference, Philadelphia, PA; pp.1–7.

Hanaki, K., Wantawin, C., & Ohgaki, S. (1990a). Effects of the activity of heterotrophs on nitrification in a suspended growth reactor. *Water Research*, *24*(3), 289–296.

Hanaki, K., Wantawin, C., & Ohgaki, S. (1990b). Nitrification at low levels of dissolved oxygen with and without organic loading in suspended-growth reactors. *Water Research*, *24*(3), 297–302.

Havelaar, A.H., & During, M. (1988). Evaluation of the Anderson Baird – Parker direct plating method for enumerating Escherichia Coli in water. *Journal of Applied Bacteriology*, *64*, 89–98.

Huang, C.S.S. (1986). Nitrification kinetics and its RBC applications. *J. ASCE. Environ. Dn.*, *108*, 473–487.

Janczukowicz, W., & Klimiuk, E. (1992). The influence of the raw wastes dosing system on technological parameters of the rotating biological disc (RBD) process. *Bioresource Technology*, *42*, 241–245.

Jirka, A., & Carter, M.J. (1975). Micro-semi – automated analysis of surface and wastewaters for chemical oxygen demand. *Analytical Chemistry*, *47*, 1397–1401.

Kinli, H. (1999). Effect of disc rotating velocity on the nitrification performance of RBC system and biofilm kinetics. *Environmental Technology*, *20*, 37–43.

Klees, R., & Silverstein, J. (1992). Improved biological nitrification using recirculation in rotating biological contactors. *Water Science and Technology*, *26*(3–4), 545–53.

Loy, T. (1988). Organic and ammonia nitrogen removal suspended solids settling and sludge stabilization using compact RBC-settling tank system, Ph-D Thesis, no. EV-88–15, AIT, Bangkok, Thailand.

Patrick, J.L. (1983). Start-up and operating characteristics of an RBC facility in a cold climate. Journal WPCF, Vol. 55, No. 10.

Rittmann, E., Suzzo, R., & Romero, B.R. (1883). Temperature effects on oxygen transfer to rotating biological contactors. *Journal Water Pollution Control Federation*, 55, 270–277.

Sagy, M., & Kott, Y. (1990). Efficiency of rotating biological contactor in removing pathogenic bacteria from domestic sewage. *Water Research*, *24*(9), 1125–1128.

Snedecor, G.W., & Cochran, W.G. (1980). Statistical methods. The Iowa State University Press, Ames, Iowa, USA.

Surampalli, R.Y., & Baumann, E.R. (1995). Sludge production in rotating biological contactors with supplemental aeration and an enlarged first stage. *Bioresource Technol.*, *54*, 297–304.

Surampalli, R.Y., Baumann, E.R. (1997). Role of supplemental aeration in improving overloaded first–stage RBC performance. *Water Air Soil Pollution*, *98*, 1–15.

Tawfik, A. (2002a). The biorotor system for post-treatment of anaerobically treated domestic sewage. Ph-D thesis, Wageningen University & Research Centre, Sub-department of Environmental Technology.

Tawfik, A., Klapwijk, A., El-Gohary, F., & Lettinga, G. (2002b). Treatment of anaerobically pretreated domestic sewage by a rotating biological contactor. *Water Research*, *36*(1), 147–155.

Tawfik, A., Klapwijk, B., El-Gohary, F., & Lettinga, G. (2002c). Treatment of anaerobically treated domestic wastewater using Rotating Biological Contactor. *Water Science and Technology*, (10), 371–376.

Tawfik, A., Klapwijk, B., Van Buuren, J., El-Gohary, F., & Lettinga, G. (2004). Physico-chemical factors affecting the E.coli removal in a rotating biological contactor (RBC) treating UASB effluent. *Water Research*, *38*(5), 1081–1088.

Tawfik, A., Zeeman, G., Klapwijk, B., Sanders, W., El-Gohary, F., & Lettinga, G. (2003). treatment of domestic sewage in a combined UASB/RBC system. Process optimization for irrigation purposes. *Water Science and Technology*, *48*(1), 131–138.

Van Buuren (1991). Post-treatment methods for effluent of UASB reactors treating domestic sewage. Internal report no. 91–3, Wageningen University, Department of Environmental Technology, The Netherlands.