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Research Article

MODEL-BASED ANALYSIS OF THE EFFECTS OF RECYCLE RATIOS ON THE PERFORMANCE OF AN A²O PROCESS

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ABSTRACT

This study presents findings of a modeling work in which the effects of internal recycle (IR) and return activated sludge (RAS) ratios on the treatment performance of an A²O process were investigated. Simulations were performed using activated sludge model no.3 extended with biological phosphorus removal processes at an influent wastewater temperature of 20°C. The results showed that not only IR ratio but also RAS ratio affects both nitrogen and phosphorus removal processes. The removal efficiencies for total nitrogen (TN) and total phosphorus (TP) changed between 71%–83% and 53%–80%, respectively, at different IR and RAS ratios. On the other hand, chemical oxygen demand (COD), total Kjeldahl Nitrogen (TKN), and total suspended solids (TSS) removal efficiencies stayed relatively constant at around 90%, 96%, and 93%, respectively, with varying IR and RAS ratios. Results indicated that an optimum set of IR and RAS ratios can be found out by activated sludge modeling. For A²O process, an IR ratio of 2.5 to 3.5 at a RAS ratio of 0.75 to 0.90 offer the best performance in terms of both TN and TP removal efficiencies.

Keywords: A²O process, internal recycle, return activated sludge, activated sludge modeling.

1. INTRODUCTION

Nitrogen (N) and phosphorus (P) are known as the main constituents that cause eutrophication in water bodies [1]. Biological nitrogen removal systems involve, of the eutrophication mechanism, nitrification and denitrification processes. In nitrification, ammonium oxidizing bacteria (AOBs) oxidize ammonium (NH_4^+) into nitrite (NO_2^-) and nitrate (NO_3^-) under aerobic conditions while nitrite and nitrate are converted into nitrogen gas (N_2) under anoxic conditions in the denitrification process [2]. Biological phosphorus removal mechanism is somewhat different than nitrogen removal, in which phosphorus accumulating organisms (PAOs) release phosphorus and accumulate by uptaking more than their own metabolic needs [3, 4]. For this purpose, anaerobic phase must be followed by an aerobic phase. In anaerobic phase, PAOs and glycogen accumulating organisms (GAOs) release PO_4-P during the accumulation of volatile fatty acids (VFAs) from the fermentation of organic matter as polyhydroxyalkanoates (PHAs). In aerobic (or anoxic) phase, PAOs take PO_4-P for growth [5].

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Activated sludge processes have long been widely used for the treatment of residential and industrial wastewaters [6], and parameters that affect microbial activity in biological processes have been topics of many research papers. Of these activated sludge processes, the A²O process (anaerobic/anoxic/aerobic configuration) have been applied widely for biological wastewater treatment [7-10].

Internal recycle (IR) ratio, also called nitrate recycle ratio, is an important operating parameter that affects denitrification performance in A²O process [11, 12]. IR carries nitrate to the anoxic zone and ensures chemical oxygen demand (COD) is used for denitrification. Considering the fact that A²O process is widely used for municipal wastewater treatment, understanding the effect of IR on the process can help the optimization process to meet the ever-increasing discharge limits [12]. The IR ratio is usually kept between 100% and 400% in biological nutrient removal processes and it is reported that the IR ratio can be changed in order to reduce effluent nitrate levels [12]. Zhang et al. [13] reported that low IR ratios lead to reduced nitrogen and phosphorus removal efficiencies, while high IR ratios result in the transport of excessive amounts of dissolved oxygen (DO) to anoxic zone in moving bed biofilm reactors (MBBRs) and suppress denitrifying PAO activity in A²O process.

Return activated sludge (RAS) ratio is an important parameter to keep mixed liquor suspended solids (MLSS) concentrations in process reactors at desired levels [14]. In certain cases such as low concentrations of readily biodegradable COD in influent, nitrate concentrations in effluent increase as a result of insufficient denitrification, which leads to recycle of nitrate to the anaerobic reactor and deteriorates biological phosphorus removal performance [15]. Chen et al. [16] reported, for A²O (anaerobic/anoxic/aerobic)-BAF (biological aerated filter) systems, that the RAS ratio must be determined depending on the influent wastewater characteristics to ensure simultaneous removal of nitrogen and phosphorus, and that RAS ratios of 100%, 400%, and 600% should be suitable for low, mid, and high C:N ratios, respectively.

The motivation of this study comes from the idea that an optimum set of IR and RAS ratios for a given set of influent characteristics and design parameters for wastewater treatment plants can be determined by modeling approach. For this purpose, activated sludge model no.3 (ASM3) extended with biological phosphorus removal processes was used for simulating an A²O process at various IR and RAS ratios, steady-state COD, TKN, TN, TP, and TSS removal efficiencies were obtained, and MLSS concentrations and sludge retention times were calculated. The treatment performance and several operating parameters under steady-state conditions were then evaluated to extract an optimum set of recycle ratios.

2. MATERIALS AND METHODS

2.1. Wastewater Characterization

Simulations were performed in an A²O process with various internal recycle (IR) and return activated sludge (RAS) ratios in the hope that an optimum value for each was extracted. For all simulations, the same wastewater characteristics were used. The total COD of the influent wastewater, which is considered to be primary effluent, was 450 mg/L. The total nitrogen (TN) and total phosphorus (TP) concentrations were 44.2 mg/L and 4.5 mg/L, respectively, corresponding to an approximate C:N:P ratio of 100:10:1. Total suspended solids (TSS) concentration was 208 mg/L. Wastewater temperature was assumed as 20°C. Influent component concentrations were predicted using the data summarized in Rössle and Pretorius [17]. A list of all components in the activated sludge modeling and their concentrations in the influent wastewater are given in Table 1.

Table 1. Influent wastewater characterization

No	Explanation	Concentration
1	Dissolved oxygen	0 mg/L as negative COD
2	Soluble inert organics	30 mg/L as COD
3	Readily biodegradable substrate	145 mg/L as COD
4	Ammonium plus ammonia nitrogen	30 mg/L as nitrogen
5	Nitrite plus nitrate nitrogen	0 mg/L as nitrogen
6	Dinitrogen (dissolved nitrogen)	0 mg/L as nitrogen
7	Phosphate-phosphorus	2.5 mg/L as phosphorus
8	Alkalinity	5 μmol HCO_3^-/L
9	Autotrophic biomass	0 mg/L as COD
10	Heterotrophic biomass	0 mg/L as COD
11	Phosphorus accumulating biomass	0 mg/L as COD
12	Particulate inert organics	25 mg/L as COD
13	Slowly biodegradable substrate	250 mg/L as COD
14	Organics stored by heterotrophs	0 mg/L as COD
15	PHA stored by PAOs	0 mg/L as COD
16	Polyphosphates stored by PAOs	0.5 mg/L as phosphorus

2.1. Treatment System

The A²O process was selected for the modeling study. The process consisted of one anaerobic reactor, one anoxic reactor, and one aerobic reactor followed by a secondary clarifier. The influent wastewater, which was assumed to be the effluent of a primary sedimentation unit, entered the anaerobic reactor, and the effluent from anaerobic reactor entered the anoxic reactor. An IR line was established to recycle nitrate from aerobic reactor to anoxic reactor. The effluent from the aerobic reactor was taken to the secondary clarifier. The RAS was taken from the bottom of the clarifier to the inlet of the anaerobic reactor. The activated sludge was wasted from the bottom of the clarifier. A flow diagram of the treatment process is shown in Fig. 1.

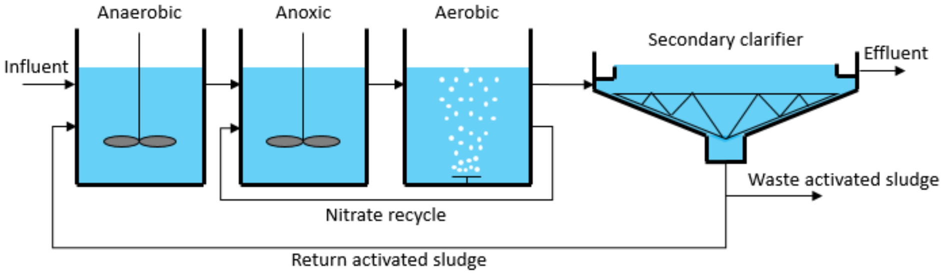

Figure 1. Flow diagram of an A²O process

The process was designed for a constant influent wastewater flowrate of 120,000 m³/d. The split ratio (the ratio of waste activated sludge flowrate to influent flowrate) was 1%, corresponding to a waste activated sludge (WAS) flowrate of 1,200 m³/d. Total hydraulic retention time of the process reactors was 5.5 hours. The depth of all process reactors was set to 5 m, and the dissolved oxygen concentration was set to 2 mg/L in the aerated reactor. The hydraulic retention time of the settler was 3 hours with a surface loading rate of 1 m³/m².h. All the dimensions and process design parameters are shown in Table 2.

Table 2. Design parameters for the A²O process

Unit Design parameter	Value
F/M ratio*	0.36 – 0.42 kg BOD / (kg MLSS.d)
Internal (nitrate) recycle flowrate	120,000 – 720,000 m³/d
Return activated sludge flowrate	90,000 – 180, 000 m³/d
Waste activated sludge flowrate	1,200 m³/d
Average MLSS concentration*	Around 5,000 mg/L
Sludge retention time*	10 – 15 days
Anaerobic reactor	
Volume	2,500 m³
Hydraulic retention time	0.5 h
Anoxic reactor	
Volume	5,000 m³
Hydraulic retention time	1.0 h
Aerobic reactor	
Volume	20,000 m³
Hydraulic retention time	4 h
Dissolved oxygen level	2 mg/L
Secondary clarifier	
Sidewall depth	3
Surface area	5,000 m²
Hydraulic retention time	3 h
Surface loading rate	1 m³/m².h

* Calculated steady-state values of these parameters change with the applied ratios of internal recycle and return activated sludge

2.3. Activated Sludge Modeling

An MS Excel VBA tool for wastewater treatment plant simulation, which was previously implemented for another purpose, was used for all simulations. The tool is based on activated sludge model no.3 by Gujer et al. [18]. ASM3 was extended with the EAWAG bio-P module for biological phosphorus removal processes by Rieger et al. [19], and corrected/verified later by Hauduc et al. [20]. The tool is capable of steady-state and dynamic simulations of a given activated sludge process with aerated and non-aerated reactor configurations. It employs a one-dimensional, ten-layered approach for modeling the secondary clarifier with Takacs' double exponential model for settling velocity of sludge. For all simulations, default values were used for all stoichiometric and kinetic parameters [20] as well as all settling parameters [21]. The integration method was selected as fourth-order Runge-Kutta with step size of 15 seconds and total simulation time of 60 days.

3. RESULTS AND DISCUSSIONS

Simulations were performed on the A²O process with various internal recycle (IR) and return activated sludge (RAS) ratios in the hope that an optimum value for each can be extracted based on the treatment performance of the system with respect to COD, TKN, TN, TP, and TSS removal efficiencies as well as sludge retention time (SRT) and mixed liquor suspended solids (MLSS) concentrations within the process reactors. All simulations were performed with the default values of kinetic and stoichiometric parameters summarized in Hauduc et al. [20].

Effluent COD concentrations were calculated between 44 and 46 mg/L, corresponding to removal efficiencies between 89.8% and 90.2% with an average value of 90%. The results showed that COD removal efficiency is a function of neither the IR nor the RAS ratio. Gallardo-

Altamirano et al. [22] reported similar COD removal efficiencies in their paper in which RAS and IR ratios were applied as 0.58 and 1.7 in phase I, and 0.74 and 2.09 in phase II, leading to COD removal efficiencies of 84% and 88% in phase I and II, respectively. Zhang et al. [13] reported COD removal efficiencies in the range of 85.66% and 88.79% in an A^2O-MBBR process operated with 100% RAS and 100%-500% IR. They reported that the effect of IR ratio on COD removal efficiency was negligible. Similarly, TKN concentrations was not under the effect of IR and RAS ratios. Calculated effluent TKN concentrations were between 1.8 to 2.0 mg/L, corresponding to an average removal efficiency of 95.7%. In terms of TSS removal, the performance of the A^2O process was satisfactory with removal efficiencies between 92.8% and 93.3% for all simulations. The results showed that TSS removal efficiency was independent of the IR and RAS ratios. A comparison of the removal efficiencies for COD, TKN, TN, NH_4-N, TP, and TSS are provided in Table 3. Results showed that removal efficiencies in this study were in agreement with those obtained in previous works.

Table 3. Comparison of removal efficiencies at various RAS and IR ratios with literature data

Process	**Wastewater**	**RAS (%)**	**IR (%)**	**Removal efficiencies (%)**						Ref.
				COD	**TN**	**TKN**	**NH_4**	**TP**	**SS**	
A^2O^a	Model	75-150	100-600	90	79.9	95.7		71.7		This study
A^2O^b	Campus wastewater	80	300		77.3		100			[23]
			500		77.6		99.5			
Modified A^2O^c	80% domestic + 20% industry wastewater	100	50	81±2.0	25±9.1		97±3.4	53±6.5	80±3.5	[24]
Modified A^2O^d	Synthetic wastewater	50	100	98	63			71		[25]
D-A^2O^e	Campus wastewater	100	200		81.37		97.44	92.45		[26]
A^2O-BAF^f	Municipal wastewater	100	100		66.5					[16]
			200		77.3					
			400		81.1					
			500		75.9					
			600		76.0					
A^2O^g	Residential area	100	100	87.6	45.9		94.9	88.4		[27]
			200	90.8	53.9		95.0	92.8		
			300	91.2	67.9		95.3	94.0		
A^2O^h	Municipal wastewater	48	213		79.7			90		[28]
		39	200		56.3			47.5		
AO^i	Municipal wastewater	-	600	96	87.1					[2]
			300	93	57.3					

[a] Anaerobic/anoxic/oxic;
[b] With pre-anoxic zone anaerobic/anoxic/oxic;
[c] With pre-anoxic selector anaerobic/anoxic/oxic;
[d] A^2O system with fiber polypropylene media;
[e] dual-anaerobic-anoxic/oxic;
[f] Conventional anaerobic/anoxic/oxic;
[g] Anaerobic/anoxic/oxic;
[h] Anaerobic/anoxic/oxic;
[I] denitrification/nitrification reactor

The MLSS concentrations ranged from 4,648 to 5,549 mg/L with minimum value observed at a RAS ratio of 0.75 and IR ratio of 6, while the maximum MLSS concentration was observed at a RAS ratio of 1.50 and IR ratio of 3. The average MLSS concentration was calculated as 5,145 mg/L for all simulations. A surface map is provided for MLSS concentration depending on recycle ratios in Fig. 2.a. The figure clearly shows that the steepest rate of change takes place in the direction of RAS ratio, which leads to the conclusion that RAS ratio is much more effective on the MLSS concentration than the internal recycle ratio. The figure also clearly shows that, at a constant RAS ratio, the MLSS concentration increases with increasing IR ratio up to 3, after which increasing the IR ratio results in reduced MLSS concentrations. For achieving the highest MLSS concentration, one must limit the IR ratio to the value of 3. The sludge retention time (SRT) ranged from 10 to 13.9 days depending on the RAS ratio (Fig. 2.b). The results showed that the internal recycle ratio has no effects on the SRT, and the main operating parameter that determines the SRT of the system was the RAS ratio at constant WAS flowrate.

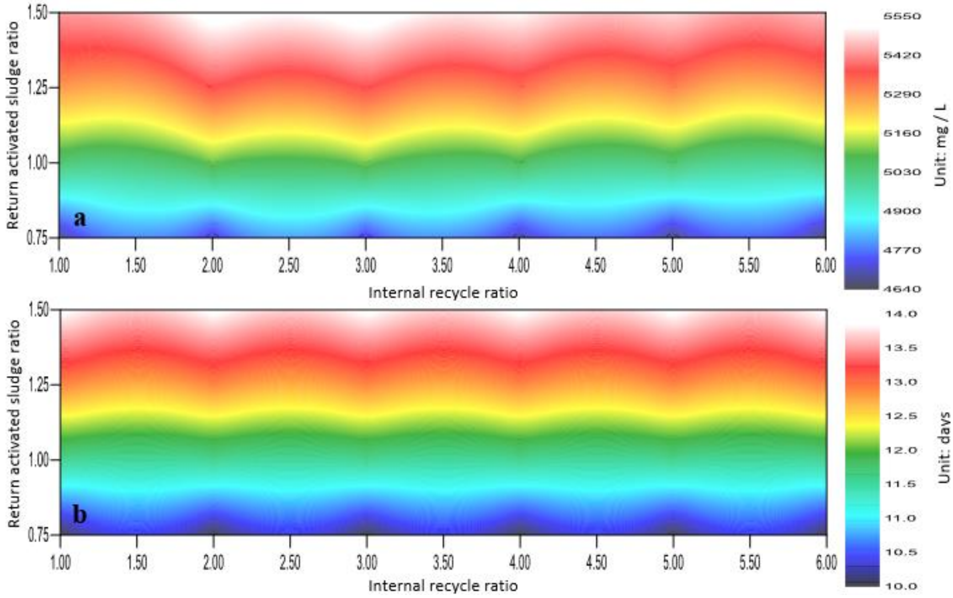

Figure 2. Surface map **a.** for MLSS concentration, **b.** for SRT depending on recycle ratios

Total nitrogen (TN) removal performance of the A²O process was satisfactory with an average removal efficiency of 79.9%±3.2%. The effluent TN concentrations ranged from 7.4 to 12.5 mg/L, corresponding to a range of removal efficiency from 71.7% to 83.3%. The highest removal efficiency was observed at the highest IR and RAS ratios, while the removal efficiency was the lowest at their lowest values. Hamad [29] reported that effluent TN concentration is a function of IR ratio, that increasing IR ratio results in reduced effluent TN concentrations, and that an IR ratio between 200% and 300% is suitable to obtain effluent TN concentrations below 10 mg/L. The change of TN removal efficiency with the IR ratio is shown in Fig. 3.a, while that with the RAS ratio is shown in Fig. 3.b. The results showed that there are no optimal values in terms of IR and RAS ratios for the best TN removal performance. The TN removal efficiency of the A²O process increases slightly with increasing RAS ratio at constant IR ratio (Fig. 3.b). The higher the RAS ratio is, the better the TN removal performance is. Tan and Ng [30] reported TN removal efficiencies of 63%, 80%, 84%, and 89%, respectively at RAS ratios of 1, 3, 5, and 10. They also reported that TN removal efficiency was satisfactorily high at RAS ratios above 3. On the other hand, the effect of IR ratio on TN removal performance was more obvious (Fig. 3.a). Considerable improvements were observed in TN removal efficiency with the increasing IR ratio. Results were in agreement with literature data that an increase in IR ratio leads to increased TN removal efficiency no matter the influent ammonium concentration is [11]. Considering the fact that the IR ratio is the ratio of the flowrate of the stream recirculating between the aerobic and the anoxic process reactors, increasing IR ratio means recycling higher amounts of nitrate nitrogen into the anoxic reactor, which, in turn, leads to reduced nitrate nitrogen concentrations in the effluent. Pelaz et al. [2] reported that increasing IR ratio in a pre-denitrification system operated at low C:N ratios improves TN removal performance considerably. The results showed that the rate of change per unit increase in IR ratio was the highest at low IR ratios. This means that the degree at which IR ratio affects the TN removal performance was higher at lower ranges. This obvious effect of IR ratio gradually diminished at higher values. Above an IR ratio 3–4, the change in TN removal efficiency with IR ratio was negligible, suggesting that an IR ratio of 3–4 could be an optimal value in terms of the cost of pumping.

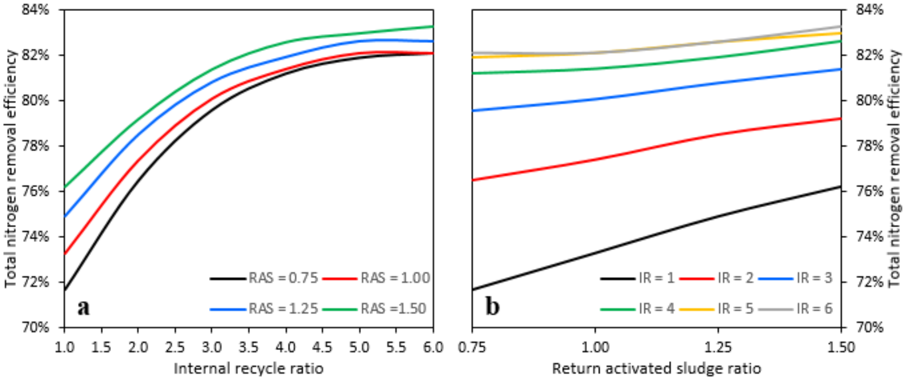

Figure 3. The change of total nitrogen removal efficiency **a.** with internal recycle ratio, **b.** with return activated sludge ratio

Effluent total phosphorus (TP) concentrations ranged from 0.90 to 2.10 mg/L for all simulations, corresponding to removal efficiencies between 53.3% and 80% with an average value of 71.7%±6.3%. The change of TP removal efficiency with IR and RAS ratio is shown in Fig. 4. In contrast to the results obtained in terms of TN removal performance, the RAS ratio had negative effects on TP removal efficiency (Fig. 4.b). Hamad [29] reported similar results that TP removal performance is deteriorated by increasing RAS ratio in an A^2O process operated at 0.15-1 RAS ratios. Lu et al. [31] stated that the reason for this behavior is the nitrate in return activated sludge recycled back to the anaerobic reactor. Considering Fig. 2.b, which shows that an increase in RAS ratio results in older sludge, one can conclude that younger sludge has higher potential of phosphorus uptake. The deteriorating effect of RAS ratio on TP removal performance was the most obvious at low IR ratios. On the other hand, increasing IR ratios at a constant RAS ratio resulted in increased TP removal performance up to an IR ratio of 3, where maximum TP removal efficiency was obtained for all RAS ratios between 0.75 and 1.5. In agreement with the results of this study, Falahti-Marvast and Karimi-Jashni [32] reported, for an A^2O-MBR process, that TP removal is insufficiently low at no external recycle (RAS = 0). On the other hand, TP removal efficiency increases up to 47.3% and 55.9% at RAS ratios of 1 and 2, respectively. They also reported that RAS ratios above 2 do not lead to considerable improvements in TP removal performance. Internal recycle ratios above 3 had a negative effect on TP removal efficiency, resulting in considerable reduction up to IR = 6. The results suggested that there is an optimal value of IR ratio for TP removal performance of the A^2O process.

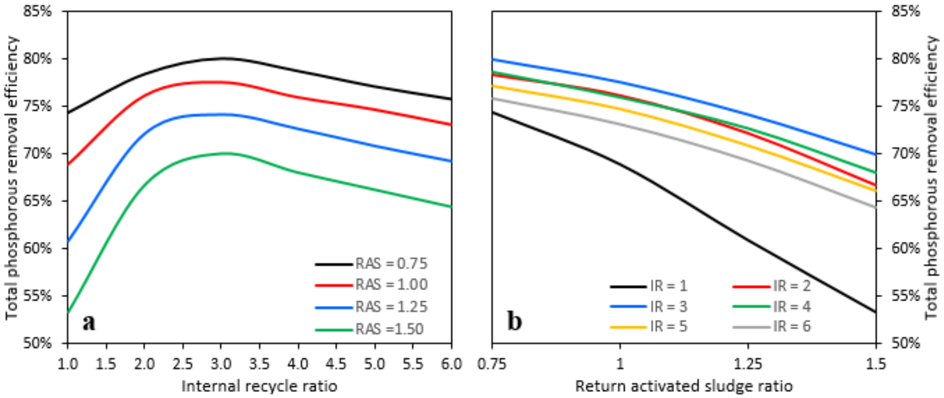

Figure 4. The change of total phosphorus removal efficiency **a.** with internal recycle ratio, **b.** with return activated sludge ratio

In order to extract an overall optimal value for each of the IR and RAS ratio for the A²O process, a surface map (Fig. 5) was prepared for TN and TP removal efficiencies at various IR and RAS ratios. The surface map clearly showed that the highest removal efficiencies are achieved at IR ratios between 2.50 and 3.50, and at RAS ratios between 0.75 and 0.90. At these ranges of recycle ratios, TN removal efficiencies were satisfactory in the range of 78% and 81%. Although higher TN removal efficiencies can be obtained at higher IR ratios, the level of TN removal performance was satisfactory at the recycle ratios mentioned above for the best TP removal performance. Besides, negligible improvement of TN removal performance was observed at IR ratios above 3. TN removal efficiencies at similar C:N ratios were obtained by Zhang et al. [13] as 52.06% at IR = 1 and 80.50% at IR = 4. They also reported that low IR ratios had negative effects on TN removal efficiency while TN removal efficiency starts decreasing at high IR ratios of 5. Baeza et al. [11] evaluated three different IR ratios as 0 (no IR), 2, and 5 and reported that IR = 0 represents minimum TN removal, IR = 2 represents an optimum operating strategy for treatment costs, and IR = 5 represents the highest limit to be applied to obtain the highest TN removal efficiencies. Besides, they reported that IR ratios above 5 means that the anoxic reactor contains the same level of dissolved oxygen as the aerobic reactor which leads to reduced denitrification capacity of the process. Results and the related literature data for TN and TP removal performance clearly indicate that an IR ratio of 2.5 to 3.5 at a RAS ratio of 0.75 to 0.90 can provide an optimized solution for both TN and TP removal efficiencies.

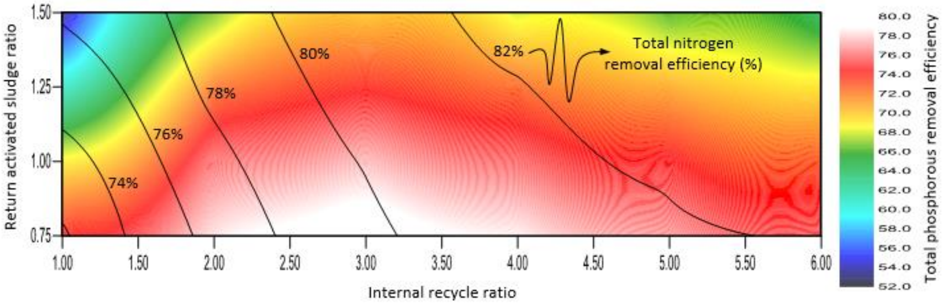

Figure 5. Total nitrogen and total phosphorus removal efficiencies at various internal recycle and return activated sludge ratios

4. CONCLUSIONS

The effects of internal recycle (IR) and return activated sludge (RAS) ratio on treatment performance was investigated in this study. For this purpose, activated sludge model no. 3 extended with biological phosphorus removal processes was used for simulating a total of 24 scenarios with six different IR ratios between 1 and 6, and four different RAS ratios between 0.75 and 1.50 in an A^2O process. Dimensions and design parameters as well as influent characteristics were the same in all simulations. Steady-state removal efficiencies for chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) as well as mixed liquor suspended solids (MLSS) concentrations and sludge retention times (SRT) were used for evaluations. Following conclusions can be withdrawn from the results of this modeling study:

- MLSS concentration in the activated sludge system is a function of both IR and RAS ratios.
- Sludge retention time is a function of only RAS ratio, while the IR ratio has no effect on SRT.
- COD, TKN, and TSS removal efficiencies are functions of neither IR ratio nor RAS ratio.
- TN removal performance of A^2O process is mainly a function of IR ratio although increasing RAS ratio (increasing SRT) also has positive effects on TN removal performance.
- In terms of TP removal efficiency, there is an optimum range of IR ratio between 2.5 and 3.5.
- Considering TN and TP removal efficiency, an optimum set of IR and RAS ratios for the best treatment performance. For A^2O process, the optimum value for IR ratio is between 2.5 and 3.5, while that for RAS ratio is between 0.75 and 0.90.

Apart from the conclusions withdrawn from the results for an A^2O process, the modeling methodology presented in this paper offers an easier and cheaper means of optimization in an activated sludge process. For operating engineers, the major challenge is usually the optimization of operating parameters to obtain an operating strategy that minimizes the costs of operation and maximizes the treatment performance. This optimization work usually requires physical experimentation in full-scale treatment plant and can be costly sometimes. On the other hand, the optimization process can be performed using a reliable model like activated sludge models as presented in this paper. The modeling approach could provide an optimum set of several operating parameters without any risks to the full-scale treatment plant if a well-calibrated modeling tool is employed.

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