

Performance improvement of a pelletisation system by pellet recirculation

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ABSTRACT

A pelletiser is a reactor in which destabilised colloids are forced to be in contact with one another through a proper degree of agitation, resulting in small but very dense pellets. These pellets form a blanket through which the incoming turbidity is trapped. In this study, the performance of an upflow pelletisation process was improved by internal pellet recirculation. With the recirculation ratio of 0.1, local river water sampled during the rainy season (100–250 NTU) needed only 1.22 mg Al l⁻¹ and 0.1 mg l⁻¹ of polymer to achieve low turbidity of less than 5 NTU. In the summer, similar polymer dose and recirculation ratio were equally effective in treating 30–90 NTU water, even without an addition of alum, to the same level. An increase in the polymer dose could enhance the settling velocity of pellets, thereby considerably extending the feed velocity through the tested columns. Due to the higher washout effect from pellet recirculation, denser pellets of up to 1.05 or even 1.49 g cm⁻³ were found with the higher Q_R/Q ratios. With pellet formation, the recirculation system in conjunction with some polymer addition could perform very satisfactorily even in the absence of alum.

Key words | coagulation, pelletisation, pellet recirculation, pellet retention time, turbidity removal

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INTRODUCTION

A pelletiser is a process in which destabilised colloids are forced to be in contact with one another through a rather high agitation, resulting in less water-bound, high-density pellets. When these pellets are formed sufficiently, they in turn form the pellet bed which can effectively trap incoming (upflow) solids through more available surface area and higher pellet settling velocity. The upflow pellet bed separator has been successfully applied for turbidity removal from a high-suspension synthetic water of 3,000 mg l⁻¹ suspended matter (Tambo & Matsui 1987, 1989; Tambo & Wang 1993*a,b,c*). It has also been tried with wastewater applications (Suzuki *et al.* 1993; Tambo *et al.* 1993, 1994). In addition, the process, with a special start-up step, was reported to be capable of good turbidity removal for a low (50) NTU synthetic water of 1- μ m kaolin-based colloidal particles (Panswad & Muangsiri 1996; Panswad & Channarong 1998), while it was also successfully applied to a real river water of 20–240 NTU in Thailand

(Panswad & Polwanich 1998). The mechanisms of this pelletisation process have been reported by several authors (Yusa & Gaudin 1964; Yusa *et al.* 1975; Tambo & Watanabe 1978; Wang & Tambo 1993; Wang *et al.* 1993).

RATIONALE AND OBJECTIVES

Higher chemical doses in terms of Al/T (aluminium:turbidity) and P/T (polymer:turbidity) are required for a less turbid water (Tambo & Matsui 1987, 1989). This results in an undesirably high aluminium content in the treated effluent. Meanwhile, the lightest and smallest pellets normally found at the top level of the pellet bed (Tambo & Matsui 1987) can be pushed up and out with the treated effluent, giving it higher turbidity and total aluminium content. In an attempt to minimise these problems, a

portion of the excess pellets from the top layer of the pellet blanket was recirculated to the bottom part of the reactor. The recirculated small and broken pellets were postulated to perform as the pellet seed for the one-by-one attachment (if the pellets had not been further severely broken by the shear forces during pumping) and the random agglomeration (if broken) of the incoming destabilised elementary particles (Wang & Tambo 1993; Wang *et al.* 1993), subsequently resulting in very compact and larger aggregates. A better process efficiency, lower chemical dosage and, therefore, less Al in the product water could then be achieved. This study aimed to test this idea in a pilot-scale pelletiser.

MATERIALS AND METHODS

The experimental apparatus consisted mainly of a constant-head tank, a rapid-mix (RM) unit of 62.5 mm inside diameter (ID) with 300 mm effective height (EH), and a fluidised-bed pelletisation reactor of 62.5 mm ID and 2,500 mm EH as depicted in Figure 1. The system was first started up by feeding a 3,000 mg l⁻¹ kaolin-based synthetic water to the reactor with some 2.43 mg Al l⁻¹ (from alum) as a coagulant and a nonionic polymer as a coagulant aid. After 1–3 h, in which a sufficient pellet mass was developed, the system was fed with the Chao Phraya River water which was taken from the Bangkok Metropolitan Waterworks Authority (BMWA) intake canal, and had varying turbidity, ranging from 100 to 250 NTU in the rainy season (which is from now on referred to as Case A) and 30 to 90 NTU in the summer (Case B). Total hardness of the river water ranged from 50 to 100 mg l⁻¹ as CaCO₃. The water was fed into the 450 rpm RM unit where the alum was introduced for destabilising the incoming colloids. The destabilised water was in turn mixed with a dose of the nonionic polymer before flowing upward from the bottom part of the reactor (in which a series of paddles provided sufficient agitation) to the overflow trough at the top. The treated water was expected to meet a 5 NTU criterion set by the Bangkok Metropolitan Waterworks Authority (BMWA) before the filtration units.

Table 1 shows the scope of the work while Tables 2 and 3 tabulate the properties of the alum and the nonionic polyelectrolyte used in this study. The reason why the particular polyelectrolyte was chosen is discussed in more detail by Panswad & Polwanich (1998). The minimum alum dosage was tried in the field by trial and error to obtain the 5 NTU product water quality. A no-alum condition was even tried for low-NTU water sampled in the summer in Case B. Generally, the process was operated for 72–144 h per run. The excess pellets were withdrawn and wasted from the port at 1,300 mm height while some of these pellets were internally recirculated by a metering pump back to the feed line to the reactor as shown in Figure 1. The recirculation ratio (Q_R/Q) was set at 0 (control), 0.1, 0.2, 0.3 and 0.4. The pellets were also sampled at different heights to determine their diameters (under a 10 × microscope), settling velocity (v_s , by thrice measuring the settled length of 300 mm of selected pellets in a cylinder and using a stop watch) and density (calculated by Stokes's law). The raw and treated waters were also sampled at 6- and 12-h intervals for the analysis of pH (by HORIBA F 13), alkalinity, turbidity (by HACH 2100 A turbidimeter) and aluminium (by Spectra AA Varian atomic absorption spectrophotometer). The pellet retention time (PRT) was calculated in a similar fashion as the solids retention time (SRT) in the activated sludge process, that is, the mass in the reactor was divided by the pellet mass discharged from the reactor per day (Panswad & Areesawangkit 2000).

RESULTS AND DISCUSSIONS

It should be noted first that the velocity expressed here is the empty bed upflow velocity (EBUV) in the pellet section of the reactor and this velocity increases with the recirculation ratio. As a result, although the higher Q_R/Q provides more pellet mass to the reactor and a better efficiency can be expected, it can also have a higher rising velocity and a negative impact on the pellet stability, thus resulting in a low effluent quality. A trade-off on the magnitude of the recirculation is therefore anticipated for the best performance.

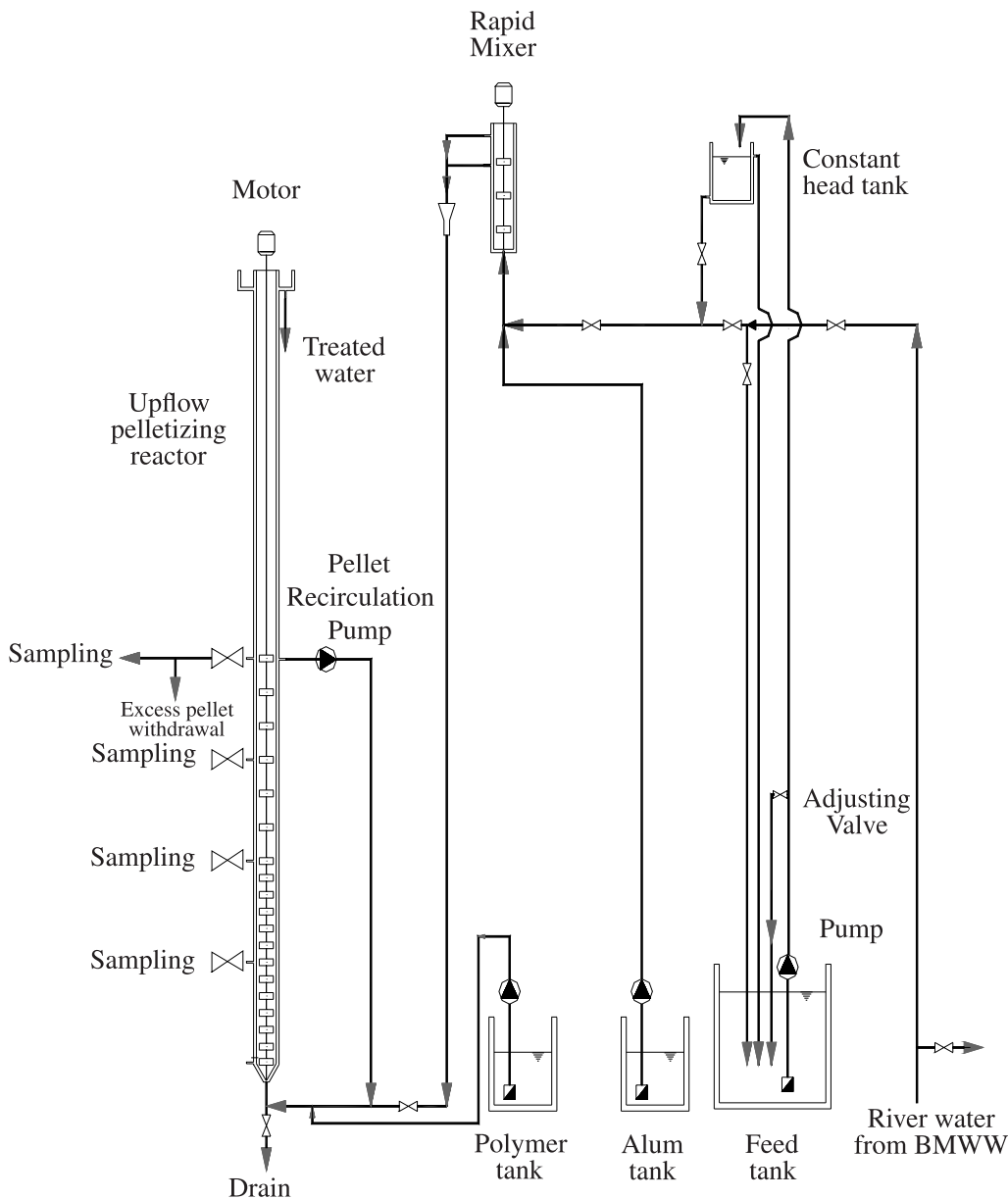


Figure 1 | The experimental setup of the pelletisation process.

Case A: 100–250 NTU (the rainy season)

The EBUV increased with the recirculation ratio and also varied with the polyelectrolyte (PE) dose as shown in Figure 2a. With the higher PE doses, the formed pellets possessed higher settling velocities (to be discussed later) and higher upflow rates were possible for an effluent with

the same quality, see Figure 2a and b. That is, when higher polymer doses were used, better throughputs could be expected from the reactors of the same size. For example, for the condition of 0.1 mg l^{-1} PE and without recirculation, the system produced an effluent of 7.9–9.7 NTU with the alum dose of $1.36 \text{ mg Al l}^{-1}$ at the EBUV of 8 cm min^{-1} , as shown in Table 4. But when the polymer dose

Table 1 | Scope of the study

Fixed variables	
Pelletiser or reactor	One type, 62.5 mm ID × 2,500 mm EH
Paddle speed	450 rpm in the RM unit 5 rpm in the reactor
Pellet height	1,300 mm (max) by the pellet withdrawal control
Independent variables	
Raw water	From the Chao Phraya River, 30–250 NTU
Alum dose	Case A: approx. 1.2–1.3 mg Al l ⁻¹ for 100–250 NTU in the rainy season Case B*: approx. 0–0.8 mg Al l ⁻¹ for 30–90 NTU in the summer
Polymer dose	0.1–0.3 mg l ⁻¹
Recirculation ratio (Q _R /Q)	0 (control) to 0.4
pH adjustment	None
Superficial velocity	8–17 cm min ⁻¹ , or 4.8–10.2 m h ⁻¹ for Case A 16–25 cm min ⁻¹ , or 9.6–15.0 m h ⁻¹ for Case B
Running time	Case A: 72 h per experimental run Case B: 72–144 h per experimental run

*Note: Experiments with no alum were also conducted for the low NTU water in Case B.

was increased to 0.3 mg l⁻¹, the process could be run, with Q_R/Q ratio of 0.4, at an EBUV of 23.8 cm min⁻¹ (equivalent to an upflow velocity of 17.0 cm min⁻¹) and could produce a better effluent quality of 1.6–1.8 NTU. However, under the same PE dose of 0.1 mg l⁻¹, the EBUV, with the Q_R/Q of 0.1, increased from 8 cm min⁻¹ in the ‘control’ (or no recirculation) to 8.8 cm min⁻¹ while the effluent turbidity dropped to 2.5–2.9 NTU,

Table 2 | Properties of the 50% liquid alum

Appearance	Liquid
Al ₂ O ₃ (%)	Min 6.5
Fe (%)	Max 0.1
Mn	Max 50 mg g ⁻¹
Cr	Max 20 mg g ⁻¹
Specific gravity	1.26

Table 3 | Properties of the nonionic polymer

Trade name	Kuriflock PN-133
Type	Nonionic polymer
Appearance	White powder
Molecular weight	12 million
Bulk density (g cm ⁻³)	0.70–0.80
Viscosity (cps) at 0.1% solution	20–40 (at 30°C)
pH at 0.1% solution	5.5–7.5
Effective pH range	5.0–8.0

indicating a higher efficiency of the system, and that was with an even lower dose of 1.23 mg Al l⁻¹. The effluent NTU decreased further to 1.0–1.1 when Q_R/Q was 0.2 and the EBUV was 9.6 cm min⁻¹. On the other hand, when the recirculation was excessive, e.g. Q_R/Q=0.4, the product water quality was degraded to 2.1–2.3 NTU. These velocities were, however, much lower than the 30–40 cm min⁻¹ found by others (Tambo & Matsui 1987, 1989; Richupan 1991; Na-nakorn 1992; Im-erbtham 1993; Panswad & Muangsiri 1996), probably because of the different characteristics of the natural water used in this study versus the synthetic waters investigated by others. With the higher polymer doses of 0.2 and 0.3 mg l⁻¹, the process was able to achieve better effluent quality regardless of the recirculation ratio, and that was even with the

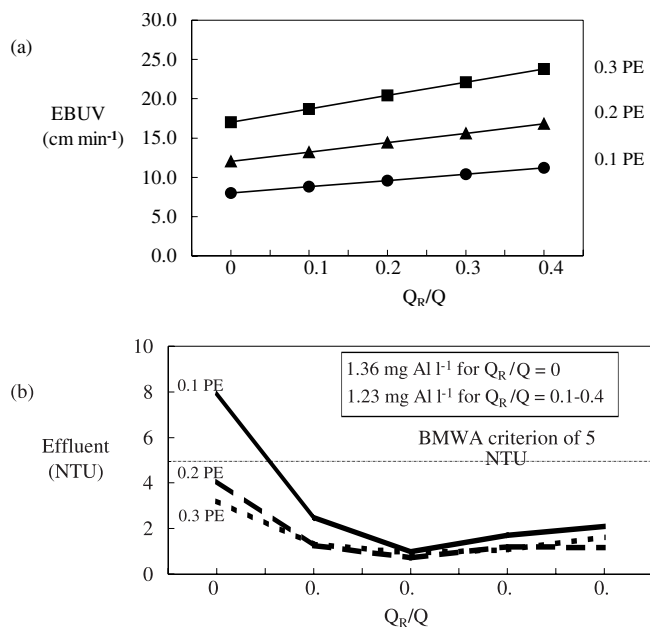


Figure 2 | Results of rainy season experiments (Case A). (a) The empty-bed upflow velocity (EBUV) in the pellet-bed zone versus the recirculation ratio. (b) The effluent NTU at different Q_R/Q values and with various polymer doses.

higher EBUV of up to 23.8 cm min⁻¹ as shown Figure 2a and b. In brief, the non-excessive recirculation of the pellet mass was beneficial to the process. In order to minimise the chemicals and the energy costs, the operating condition of 0.1 mg l⁻¹ PE and the Q_R/Q of 0.1 was suggested for this Case A.

With the recirculation of the pellet mass (PM) back to the system, the process tended to perform better right from the beginning after the start-up stage, as shown in Figure 3a and b. Less NTU was evident from the first hours with Q_R/Q of 0.2. The time to reach the steady state ($t_{s/s}$) or a constant effluent NTU was also minimised, see Figure 4a, and a short $t_{s/s}$ was achievable at the high Q_R/Q if a sufficient PE dose was used. Moreover, as Figure 4b shows, the amount of time required to get the criterion 5 NTU effluent quality (t_5) was also lessened with polymer doses. A similar pattern as that in Figure 4a was apparent and with 0.2–0.3 mg l⁻¹ PE the system could produce an effluent with even less than 5 NTU right from the start for $Q_R/Q = 0.2$ –0.3. This demonstrated the significance of the polymer dose on the system (Bratby 1980; Schwayer 1981; Tambo & Matsui 1987; Hughes 1990; Im-erbtham 1993)

and the effectiveness of the recirculation on the performance of this process. These data on $t_{s/s}$ and t_5 can be a very useful guideline for operators in field conditions.

Too small and too light pellets are to be pushed upward and out of the process. Only those that can tolerate the up-push (washout) of the rising flow manage to stay in the bed or the system. Table 4 shows the average settling velocity of several pellets taken randomly from the **top** (and **critical**) layer of the pellet bed. It was clear that the recirculation slightly increased the settling velocity (v_s) of these critical pellets, for example from 8.4 to 10.2 cm min⁻¹ with the addition of 0.1 mg l⁻¹ PE for the Q_R/Q ratio of 0 (control) to 0.4, respectively. On the other hand, the effect of the polymer addition on v_s was more pronounced. For example, for the $Q_R/Q = 0.2$ condition, v_s increased from 9.3 to 14.3 and 20 cm min⁻¹ for the three PE doses. This finding once again demonstrated the great impact of the polymer on the potential performance of the pelletisation process. Upon comparing these v_s data and the EBUV in Figure 2a, it is clear that they were comparable and a clear effluent was therefore possible.

The diameters of these critical pellets for the various conditions, as shown in Table 4, were not much different, ranging from 0.26 to 0.27, 0.26 to 0.27 and 0.27 to 0.28 mm for the cases of 0.1, 0.2 and 0.3 mg l⁻¹ PE, respectively. These data agreed with the results reported earlier in the studies with the low NTU real surface water (Panswad & Polwanich 1998; Panswad & Areesawangkit 2000). The calculated pellet density of the pellets was shown to be 1.03 (with no recirculation) to 1.04 (with Q_R/Q of 0.4), 1.05 to 1.07, and 1.06 to 1.08 g cm⁻³ for the three conditions, respectively. These were in the range found by some authors, 1.002–1.10 g cm⁻³ (Tambo & Watanabe 1978; Tambo & Wang 1993a), but lower than some others, 1.08–1.25 g cm⁻³ (Tambo & Matsui 1987, 1989).

It is believed that the amount of the pellet mass present in the reactor is a key factor in the turbidity removal efficiency. The process performance in terms of PME (the pellet mass efficiency) or the percentage of the turbidity removal, %T_r, per pellet mass in the reactor, g, is shown in Table 4. The PME increased with the recirculation ratio of 0 to 0.4 for all polymer addition conditions.

Table 4 | The experimental average results during the last 24 hours under the high (100–250) NTU condition

Q _R /Q	Alum mg l ⁻¹	EBUV cm min ⁻¹	pH		Alkalinity mg l ⁻¹ CaCO ₃				NTU		Eff	%	PM g	PME	PRT d	Pellet*			Eff AI μg l ⁻¹
			RW	RM	Eff	RW	RM	Eff	RW	RM						Eff	Φ mm	v _s	
(a) 0.1 mg l⁻¹ polymer																			
0	1.36	8	7.62	7.78	7.91	72	64	64	100–129	7.9–9.7	92.3	77.71	1.19	2.55	0.26	8.39	1.03	160	
0.1	1.23	8.8	7.63	7.81	7.92	75	67	67	120–152	2.5–2.9	98.0	77.57	1.26	2.49	0.27	9.00	1.03	80	
0.2	1.23	9.6	7.62	7.81	7.93	74	67	67	104–126	1.0–1.1	99.1	72.36	1.37	2.25	0.26	9.33	1.04	80	
0.3	1.23	10.4	7.64	7.80	7.92	74	66	66	110–152	1.7–1.8	98.6	71.66	1.38	2.39	0.26	10.06	1.04	85	
0.4	1.23	11.2	7.63	7.81	7.95	76	67	68	120–172	2.1–2.3	98.4	67.38	1.46	2.08	0.26	10.21	1.04	83	
(b) 0.2 mg l⁻¹ polymer																			
0	1.36	12.0	7.66	7.85	7.97	75	67	66	117–166	4.1–4.6	96.9	86.00	1.13	2.46	0.26	12.44	1.05	107	
0.1	1.23	13.2	7.61	7.80	7.95	74	67	67	110–176	1.3–1.4	99.0	84.50	1.17	2.20	0.27	13.43	1.05	87	
0.2	1.23	14.4	7.61	7.76	7.87	72	65	65	171–207	0.7–0.9	99.6	84.66	1.18	2.14	0.27	14.26	1.05	82	
0.3	1.23	15.6	7.61	7.81	7.89	73	67	66	155–250	1.2–1.5	99.3	76.74	1.29	2.15	0.26	14.51	1.06	86	
0.4	1.23	16.8	7.61	7.76	7.84	72	64	65	145–195	1.2–1.4	99.3	72.03	1.38	1.83	0.26	16.34	1.07	86	
(c) 0.3 mg l⁻¹ polymer																			
0	1.36	17.0	7.59	7.75	7.86	74	67	66	126–194	3.2–3.7	97.8	98.18	1.00	1.80	0.28	18.10	1.06	115	
0.1	1.23	18.7	7.58	7.73	7.80	74	66	66	120–165	1.3–1.6	99.0	88.08	1.12	1.72	0.27	19.29	1.07	82	
0.2	1.23	20.4	7.68	7.83	7.87	74	67	67	132–192	0.9–1.8	99.0	86.94	1.14	1.65	0.28	20.00	1.07	80	
0.3	1.23	22.1	7.64	7.80	7.87	74	67	67	109–150	1.1–1.4	99.1	85.90	1.15	1.63	0.28	21.34	1.08	75	
0.4	1.23	23.8	7.60	7.79	7.91	75	68	69	109–195	1.6–1.8	98.9	80.33	1.23	1.50	0.28	21.91	1.08	77	

Notes: EBUV, the empty bed upward velocity in the pellet-bed zone, cm min⁻¹.

RW, raw water.

RM, after rapid-mix unit.

Eff, treated effluent.

PM, pellet mass in the reactor, g.

PME, pellet mass efficiency in terms of % turbidity removal per g of PM.

PRT, pellet retention time, days, or pellet mass in reactor/pellet mass discharged per day.

*Collected from the critical or top layer of pellet blanket.

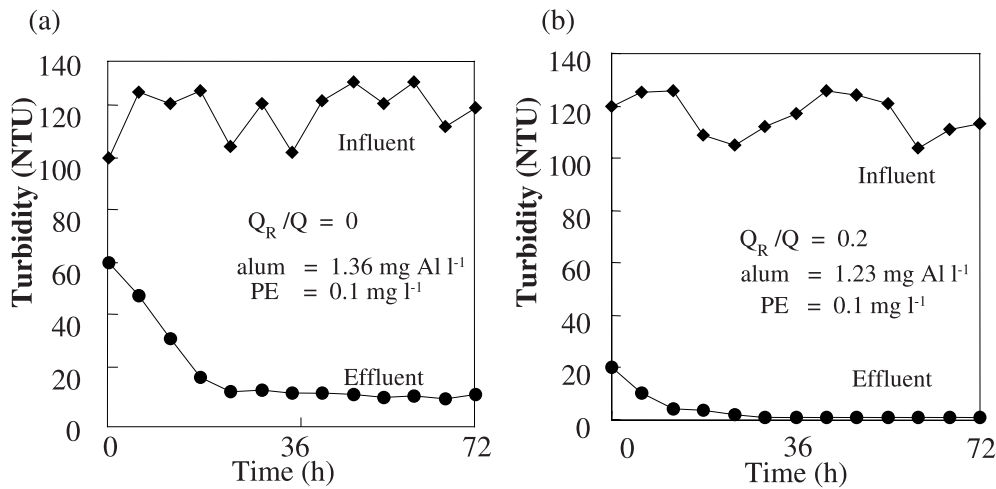


Figure 3 | Typical profile of the NTU of the raw water and the treated effluent versus run time (Case A). (a) No pellet recirculation. (b) With recirculation ratio of 0.2.

The PM in the reactor decreased with the Q_R/Q ratio because of the higher washout impact of the higher EBUV. It is noted that due to the higher feed rate, the solids

loading to the reactor was greater for the high PE than for the low PE condition. These figures related to the PRT values for the three polymer doses. They were approximately in the range of 1.03–3.75 days found by Panswad & Areesawangkit (2000). With the higher Q_R/Q , the PRT decreased, that is, a lower pellet mass was required for the same solids input (which must equal the solids output at the steady state). In other words, the higher EBUV resulting from the higher Q_R/Q will perform a selection process and get rid of the small and light pellets so that the reactor ends up having only the heavy pellets, with less overall mass but higher efficiency. It is also apparent that the pellet mass formed in the reactor increased with the PE dose because the polymer can provide a strong bonding between the destabilised elementary particles, and the dense pellets can be formed. In this aspect, the effect of the polymer on the PRT was greater than that of the pellet recirculation.

Although it is still very debatable, the aluminium content in treated water has recently been of great public interest due to concern over Alzheimer's disease. It is evident in Table 4 that, although the Al concentration of the product water was lower than the WHO standard of 200 $\mu\text{g l}^{-1}$ in all cases, the pellet recirculation could effectively reduce the Al concentration, thereby confirming once again its worthiness for the application.

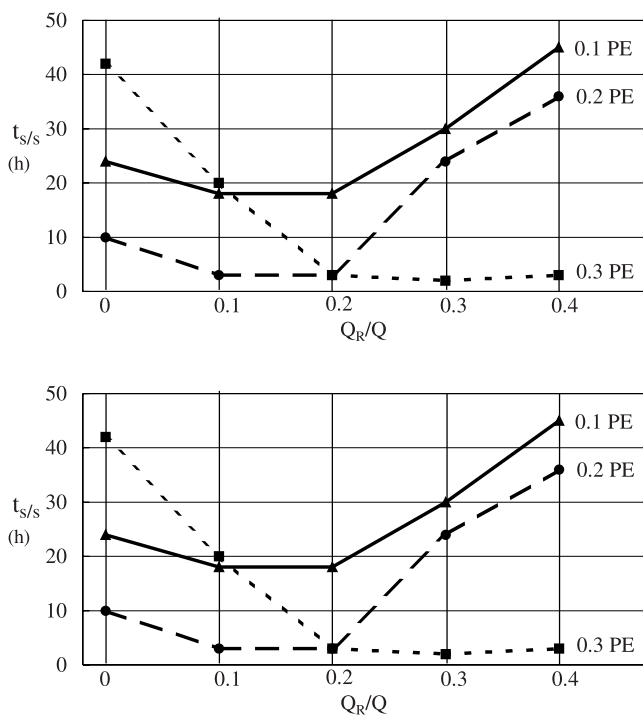


Figure 4 | The relationship between startup time and the recirculation ratio at different polymer doses (Case A). (a) $t_{s/s}$ versus Q_R/Q ratio. (b) t_5 versus Q_R/Q ratio. $t_{s/s}$ = time required to produce a steady state or a constant NTU in the effluent; t_5 = time required to achieve 5 NTU effluent at different Q_R/Q and polymer doses.

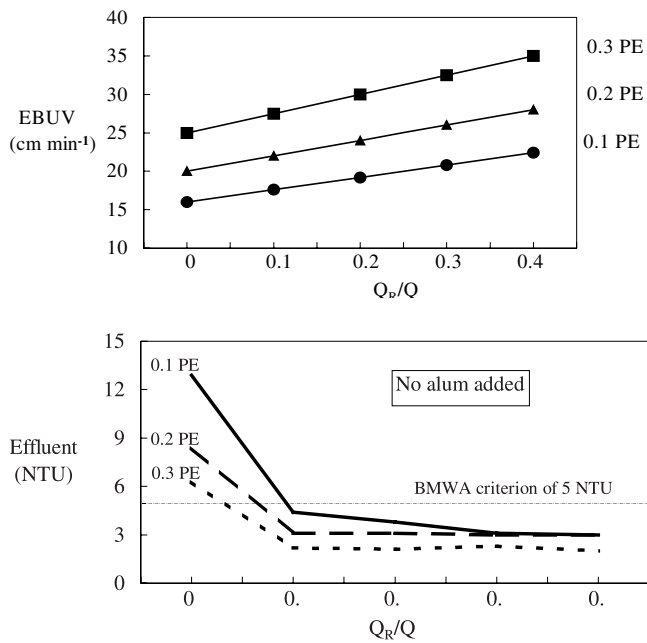


Figure 5 | Result of summer experiments (Case B). (a) The empty-bed upflow velocity (EBUV) in the pellet-bed zone versus the recirculation ratio. (b) The effluent NTU at different Q_R/Q values and with various polymer doses.

Case B: 30–90 NTU (the summer)

The rising velocity for the no-pellet recirculation condition ranged from 16 to 25 cm min⁻¹ for the PE doses of 0.1 to 0.3 mg l⁻¹, respectively. The related figures for the

Q_R/Q ratio of 0.4 were 22.4, 28 and 35 cm min⁻¹, respectively, as shown in Figure 5a. These were higher than those in Case A even though no alum was used in the process because of the lower solids load to the systems. A higher flowrate is then possible for the low NTU feed water (Panswad & Areesawangkit 2000).

The pellet recirculation obviously improved the system efficiency but no optimum Q_R/Q was evident in this case (Figure 5b). An operating condition of 0.1 mg l⁻¹ PE and 0.1 Q_R/Q ratio, but without alum application, was recommended. With only polymer addition, as Figure 6a and Table 5 show, the process could still remove a certain amount of turbidity from the feed water. However, no improvement with time was observed. After the start-up process, a dose of polymer was continuously added to the system with a sufficiently high P/T ratio and turbidity removal resulted. However, when a dose of the alum was used in conjunction with the polymer, a clearer effluent was achieved without the pellet recirculation as shown in Table 5. It is noted that the alum dose (which created a certain destabilisation of the colloids before the pelletisation process) also decreased with the increase of the polymer.

Figure 7a and b shows that pellet recirculation could greatly reduce $t_{s/s}$ and t_5 for Case B, especially for the low PE dose of 0.1 mg l⁻¹. However, an optimal Q_R/Q ratio was not seen for this case, especially for the 0.3 mg l⁻¹ PE

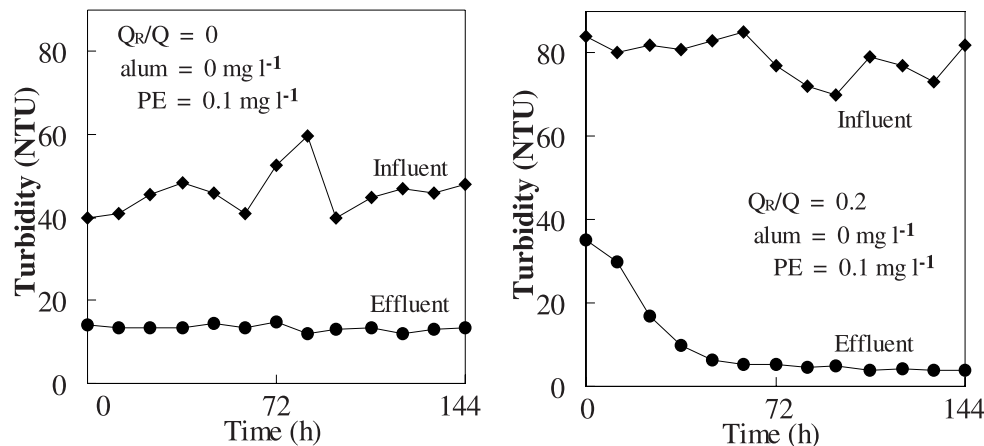


Figure 6 | Typical profile of the NTU of the raw water and the treated effluent versus run time (Case B). (a) No pellet recirculation and no alum (b) with recirculation ratio of 0.2 and no alum.

Table 5 | The experimental average results during the last 24 hours under the low (30–90) NTU condition

Q _R /Q	Alum mg Al l ⁻¹	EBUV cm min ⁻¹	pH		Alkalinity mg l ⁻¹ CaCO ₃				NTU		Eff	%	PM g	PME	PRT d	Pellet*			Eff Al μg l ⁻¹
			RW	RM	Eff	RW	RM	Eff	RW	RM						Eff	φ mm	V _s	
(a) 0.1 mg l ⁻¹ polymer																			
0	0.85	16.0	7.47	7.70	7.80	100	95	96	40–47	4.4–4.7	89.5	64.47	1.39	3.90	0.23	17.20	1.09	73	
0	0	16.0	7.47	—	7.55	82	—	82	41–53	12.9–13.4	72.0	70.10	1.02	—	0.18	17.40	1.15	73	
0.1	0	17.6	7.45	—	7.56	82	—	82	72–91	4.4–4.7	94.4	65.26	1.45	3.30	0.17	17.31	1.17	72	
0.2	0	19.2	7.46	—	7.55	82	—	82	70–85	3.8–4.5	94.6	63.63	1.48	3.33	0.18	19.47	1.17	78	
0.3	0	20.8	7.45	—	7.55	82	—	83	30–63	3.1–3.9	92.5	62.07	1.49	3.32	0.17	21.17	1.20	71	
0.4	0	22.4	7.45	—	7.56	83	—	83	35–67	3.0–3.6	93.5	60.76	1.54	3.17	0.17	22.83	1.21	74	
(b) 0.2 mg l ⁻¹ polymer																			
0	0.51	20.0	7.48	7.77	7.88	85	82	82	40–51	3.1–4.3	91.9	97.47	0.94	3.40	0.24	20.91	1.10	82	
0	0	20.0	7.49	—	7.62	84	—	84	42–53	8.4–9.3	81.4	99.79	0.82	—	0.18	21.15	1.18	71	
0.1	0	22.0	7.46	—	7.56	85	—	85	40–53	3.1–3.9	92.5	94.93	0.97	3.29	0.18	22.43	1.19	73	
0.2	0	24.0	7.44	—	7.55	83	—	84	39–51	3.1–4.2	91.9	94.57	0.97	3.27	0.17	25.63	1.24	69	
0.3	0	26.0	7.45	—	7.53	83	—	83	42–61	3.0–3.7	93.9	92.35	1.01	3.13	0.18	27.16	1.24	75	
0.4	0	28.0	7.45	—	7.55	83	—	84	39–48	3.0–3.7	92.3	90.23	1.02	3.05	0.17	28.33	1.24	70	
(c) 0.3 mg l ⁻¹ polymer																			
0	0.34	25.0	7.44	7.84	7.96	84	82	82	44–64	3.5–4.1	93.0	95.85	0.97	2.93	0.23	25.13	1.13	80	
0	0	25.0	7.45	—	7.57	84	—	84	40–50	6.3–6.7	85.6	104.38	0.82	—	0.17	26.55	1.26	69	
0.1	0	27.5	7.45	—	7.56	84	—	84	40–66	2.2–2.6	95.5	95.55	1.00	2.92	0.16	28.61	1.31	71	
0.2	0	30.5	7.44	—	7.54	83	—	84	47–66	2.1–3.3	95.2	94.91	1.00	2.78	0.16	29.74	1.32	70	
0.3	0	32.5	7.45	—	7.55	84	—	84	54–69	2.3–3.5	95.3	92.44	1.03	2.77	0.17	33.04	1.33	68	
0.4	0	35.0	7.45	—	7.55	82	—	83	52–66	2.0–3.1	95.7	90.50	1.06	2.69	0.17	36.44	1.39	73	

Note: All nomenclatures are similar to those described in Table 4.

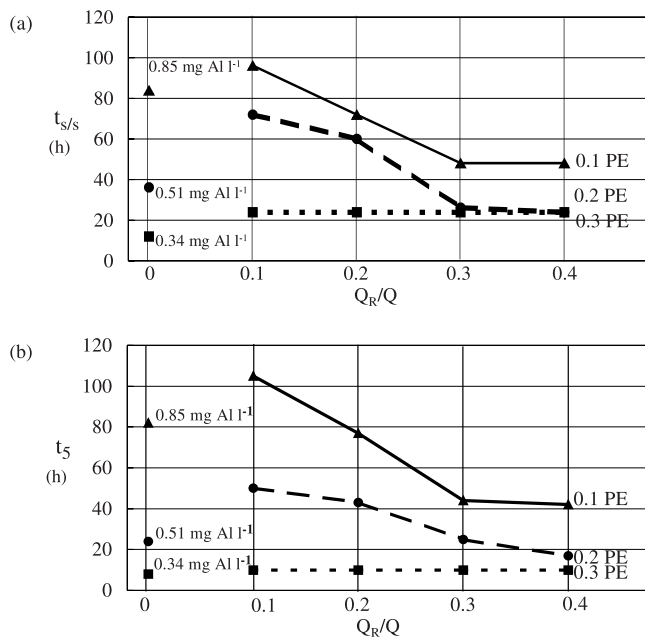


Figure 7 | The relationship between startup time and the recirculation ratio at different polymer doses (Case B). (a) $t_{s/s}$ versus Q_R/Q ratio. (b) t_5 versus Q_R/Q ratio. $t_{s/s}$ =time required to produce a steady state or a constant NTU in the effluent; t_5 =time required to achieve 5 NTU effluent at different Q_R/Q and polymer doses.

condition. The $t_{s/s}$ and t_5 values for this case were, however, much longer than those in Case A. As long as 96 hours was needed for $t_{s/s}$ for 0.1 mg l⁻¹ PE and 0.1 Q_R/Q ratio. The low NTU (or solids) input into the system may explain this finding. With the higher Q_R/Q ratio, which means more pellets (or rather solids) were entering the reactor, the shorter $t_{s/s}$ and t_5 could be achieved.

The settling velocities of the **critical** pellets at the top of the bed for Case B are shown in Table 5. Unlike Case A, the pellet recirculation increased the pellet settling velocities. This was definitely a selective result through the pellet washout from the high EBUV at different Q_R/Q values, as shown in Figure 5a. With the lower solids loading to the reactor and without the alum addition (in which no water-bound floc was produced), the pellets in Case B were smaller in diameter but higher in density. The diameters of the alum-added pellets were always larger than their counterparts without the alum addition. On the other hand, the corresponding densities of the pellets in alum-added systems were consistently lower than those

without alum. This extremely high density was essential if the small pellets at the critical layer were to survive the strong up-push or washout effect of the higher EBUVs.

The pellet mass in the reactor in Case B (see Table 5) was in the same range as in Case A (Table 4). A slightly lower PM was, however, seen for 0.1 mg l⁻¹ PE in Case B and this resulted in the higher PME of 1.02 to 1.54% T_r g⁻¹ at $Q_R/Q = 0$ to 0.4, respectively. For other cases of 0.2 and 0.3 mg l⁻¹ PE, due to the lower solids loading to the process than in Case A, the PMEs for Case B were lower. The related PRT was therefore higher (because of fewer pellets or solids mass to be discharged per day) and ranged from 2.7 to 3.4 days as compared with 1.5 to 2.5 days in Case A.

The Al concentration in the product water in Case B was again always less than the WHO standard, ranging from 73 to 82 $\mu\text{g l}^{-1}$ with the alum application and from 68 to 78 $\mu\text{g l}^{-1}$ without the alum. The recirculation in this latter case could not naturally reduce the Al content because no alum was used under these scenarios.

CONCLUSIONS

The upflow pelletisation system performed better with the internal pellet recirculation (Q_R/Q) of 0.1–0.4. With the real river water of 100–250 NTU in the rainy season, the process with some 1.2 mg Al l⁻¹ (from alum) was suggested to be used with the nonionic polymer dose of 0.1 mg l⁻¹ and at the Q_R/Q of 0.1. In the summer, during which the turbidity decreased to 30–90 NTU, the same ratio of Q_R/Q and 0.1 mg l⁻¹ PE, though without alum addition, were recommended to produce the <5 NTU water. With a higher polymer dose, an increase in the flowrate to the reactors was possible, making the system capable of having better throughput from the same reactor. As high as 17 and 25 cm min⁻¹ (10.2 and 15.0 m h⁻¹) of the nominal velocity in the reactor were possible for the cases of the rainy season and summer, respectively. With the pellet recirculation put into use, the time required to reach the 5-NTU effluent criterion was dramatically reduced from some 15 hours to almost zero and from some 50–100 hours to 10–25 hours for both

cases, respectively. The system efficiency in terms of PME increased with the recirculation ratio while the PRT decreased. The polymer addition was also shown to be essential in pellet formation and, as a result, to improve the process performance.

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ABBREVIATIONS AND NOTATION

ρ = pellet density, g cm^{-3}
 Al/T = aluminium-to-turbidity ratio
 EBUV = empty bed upward velocity in the pellet-bed zone, cm min^{-1}
 Eff = treated effluent
 PE = polyelectrolyte
 PM = pellet mass in the reactor, g
 PME = pellet mass efficiency in terms of % turbidity removal per g of PM
 PRT = pellet retention time, days, or pellet mass in reactor/pellet mass discharged per day
 P/T = polymer-to-turbidity ratio
 Q_R/Q = recirculation ratio
 RM = rapid-mix unit
 RW = raw water
 t_5 = time to achieve the required 5-NTU effluent quality
 $t_{s/s}$ = time to reach steady state, hours
 vs = settling velocity, cm min^{-1}

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