

Pellet mass loading and pellet retention time for turbidity removal in a pelletisation process

Thongchai Panswad and Kultida Areesawangkit

ABSTRACT

A pilot scale pelletiser, after a special start-up with 3,000 mg/l kaolin, was tested continuously for 72–84 h for each run with water from a local river, the Chao Phraya, for its turbidity removal efficiency at different upflow velocities, i.e. (A) 9.6 and 15 m/h for the 'low' turbidity feed water of 30–60 NTU in the summer season, and (B) 6 and 9.6 m/h for the 'high' turbidity influent of 100–200 NTU in the rainy season. Alum, in doses of 3–10 mg/l for Case A and 19–26 mg/l for Case B, and 0.3 mg/l nonionic polymer, were used as the coagulant and coagulant aid for the two cases, respectively. Alternatively, the polymer, at doses of 0.1–0.3 mg/l, was used as the sole coagulant in the process.

The aluminium to turbidity (Al/T) ratios were 0.004–0.015 and 0.014–0.022 g/g SS for Cases A and B, respectively. The polymer to turbidity ratio (P/T) was set at 0.0054–0.0059 and 0.0020–0.0030 g/g SS for the two cases, respectively. The pellet mass loading, in terms of the turbidity removal per pellet mass, was 0.40–0.76 and 0.13–0.21 (g SS/day)/g, or 0.90–1.21 and 0.13–0.20 raw water NTU/g, for the two cases respectively. The pellet retention time (PRT) or pellet age (θ_c), required to produce water of better than 5 NTU quality, was 4.4–11.9 and 1.3–3.7 days for the two scenarios. The nonionic polymer was used as the destabilising coagulant with less satisfactory results. The PRT under this condition was, however, 4.8–11.9 and 2–3 days for Cases A and B, respectively. It is noted that the pellet size for both cases was similar, i.e. 0.18–0.22 mm diameter, with a corresponding high density of 1.06–1.12 g/cm³.

Key words | coagulation, pellet mass loading, pellet retention time, pelletisation process, turbidity removal

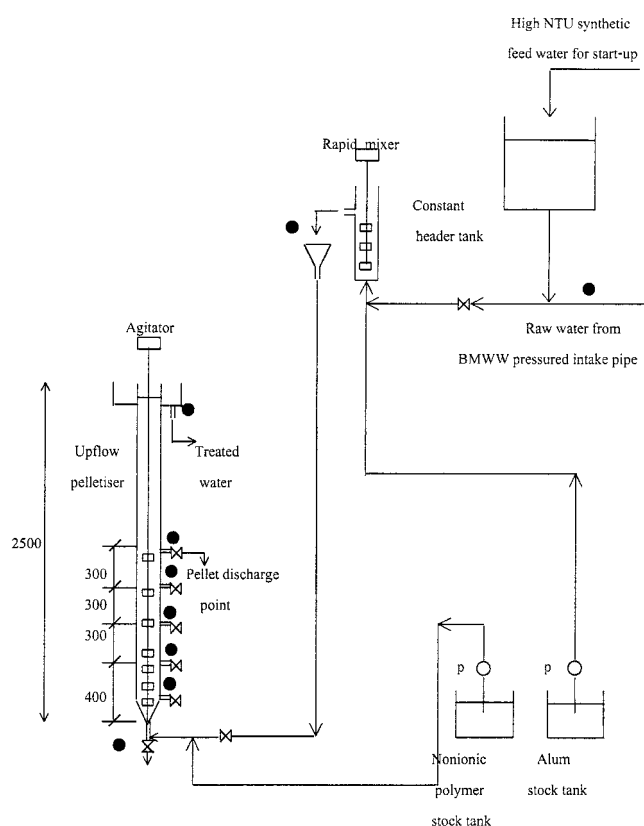
Thongchai Panswad
Kultida Areesawangkit
Department of Environmental Engineering,
Chulalongkorn University,
Bangkok 10330,
Thailand
Fax: 662-2186666;
E-mail: pthongch@chula.ac.th

INTRODUCTION

In a normal water treatment operation, the flocculation process is essential before a sedimentation unit, to enhance the floc size and therefore its settling velocity (O'Melia 1972). In the pelletisation system, however, the sedimentation tank is removed and pellets of very high density are needed to rapidly settle in the pelletisation reactor, see Figure 1. The destabilised water-bound floc, resulting from the chemical coagulation, is further broken down in size through agitation by paddles in the pelletisation reactor and reattaches to form pellets. This can be achieved by one-by-one attachment of the destabilised colloids under the metastable state (Yusa & Gaudin 1964;

Yusa *et al.* 1975; Tambo & Matsui 1987, 1989; Tambo & Wang 1993a,b; Wang & Tambo 1993; Wang *et al.* 1993). The process can therefore produce a very good effluent quality with reduced capital and operating costs.

The fluidised-bed pellet reactor was successfully used to remove turbidity from synthetic high-turbidity (approximately 3,000 NTU) raw water (Tambo & Matsui 1987, 1989; Tambo & Wang 1993a,b,c). The process was also satisfactorily applied in clarification in biological wastewater treatment processes (Suzuki *et al.* 1993; Tambo *et al.* 1993, 1994). This system was originally believed not to be applicable to a low NTU feed water



Note ● sampling points

Figure 1 | Process setup for the experiment.

because insufficient pellet mass was likely to be developed in the reactor. However, Panswad & Channarong (1998) have reported a successful experiment with a synthetic water of only 50 NTU, which was mainly composed of kaolin-based 1 μm diameter colloids. The removal efficiency was found to be as high as 98% with a dosage of only 4 mg/l PACl (polyaluminium chloride). A pilot scale pelletiser was also tried successfully in operations running for 6 and 72 h with river water in Thailand (Panswad & Polwanich 1998). The feed turbidity in this experiment was from only 15 to as high as 240 NTU.

OBJECTIVE

In this study, the system was tested with water from the Chao Phraya river (30–200 NTU) and run until a steady

state condition was achieved (72–84 h). A polymer can be used as a coagulant in a water treatment process (Bratby 1980). As a result, besides using alum and a nonionic polymer as the coagulant and coagulant aid, respectively, the system was also investigated with a nonionic polymer as the sole coagulant. In addition, the pellet mass loading (PML) and the pellet retention time (PRT) or pellet age (θ_c) were suggested as criteria to determine the process performance in terms of turbidity removal. Since these two parameters represent a relatively new approach, various conditions over a broad spectrum, e.g. using different chemicals at various doses and upflow velocities, were tried in this preliminary study with river water.

MATERIALS AND METHODS

Figure 1 illustrates the experimental apparatus used in this study. It consists mainly of a constant header tank, a rapid-mix plastic unit of 62.5 mm inner diameter (ID) and 300 mm effective height (H), and a fluidised-bed pelletisation reactor of 54 mm ID and 2500 mm H.

The system was first started up by introducing a feed water of 3,000 mg/l kaolin to the reactor with coagulant and coagulant-aid doses according to that particular experiment. The synthetic high NTU raw water was fed into the constant header tank prior to being discharged to the 450 rpm rapid-mix (RM) unit where the alum was introduced. The destabilised water was then mixed with a 0.3 mg/l dose of a nonionic polymer before entering the bottom part of the fluidised bed reactor and flowing upwards through the height of the reactor, in which an agitator provided sufficient mixing for an effective pelletisation process. With this method, the pellets were formed within 1–3 h. Then the process was fed with the river water which came from the Bangkok Metropolitan Water Works (BMWW) pressurised intake pipe and had varying turbidity, ranging from approximately 34 to 56 NTU and 99 to 193 NTU in the summer and rainy seasons, respectively. The treated water then flowed through the outlet and was allowed to drain to a nearby gutter. The effluent requirement in terms of NTU was set at 5 by the Bangkok Metropolitan Waterworks Authority (BMWA).

Table 1 | Experimental conditions.**Fixed variables:**

Reactor	One type, 54 mm ID × 2500 mm H
Paddle speed:	
in RM unit	450 rpm
in pelletiser	5 rpm
Pellet height	Kept at 1300 mm (max) by pellet withdrawal

Independent variables:

Raw water	Chao Phraya river, 30–200 NTU, depending on season
Chemical dose:	
Case A1	3 to 10 mg/l of alum plus 0.3 mg/l of nonionic polymer for summer season (30–60 NTU)
Case A2	0.1 to 0.3 mg/l of nonionic polymer as coagulant for summer season
Case B1	18.7 to 25.8 mg/l of alum plus 0.3 mg/l of polymer for rainy season (100–200 NTU)
Case B2	0.1 to 0.3 mg/l of nonionic polymer as coagulant for rainy season
Upflow feed velocity:	9.6 and 15 m/h for Case A (summer season) 6 and 9.6 m/h for Case B (rainy season)
pH adjustment	None
Run time	72–84 h for each experiment

Dependent variables:

Detention time:	6 and 25 min in RM unit and pelletiser at feed velocity of 6 m/h 3.75 and 15.6 min in RM unit and pelletiser at feed velocity of 9.6 m/h 2.4 and 10 min in RM unit and pelletiser at feed velocity of 15 m/h
Water quality	Dependent on operating conditions
Pellet characteristics	Dependent on operating conditions

Experimental conditions, as shown in Table 1, were set according to the past experiences of the authors (Panswad & Channarong 1998; Panswad & Polwanich 1998). Tables 2 and 3 give the properties of the alum and

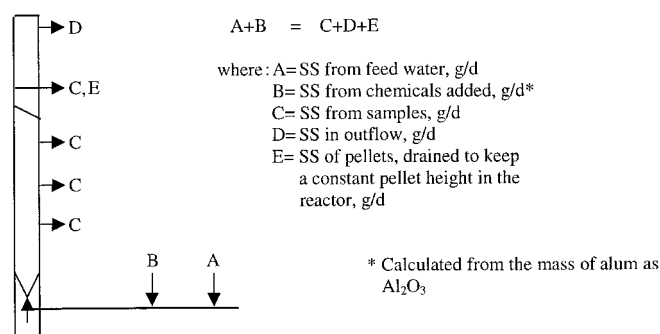
the nonionic electrolyte used in this research. Pellet samples were taken at 0, 400, 700, 1,000 and 1,300 mm pellet height at 12 h intervals for analysis of suspended solids (by a gravitational method), diameter (using a

Table 2 | Properties of the 50% liquid alum.

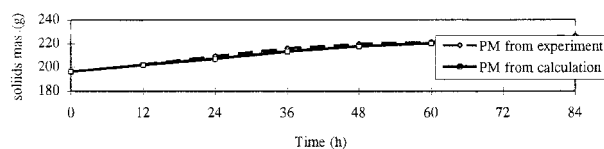
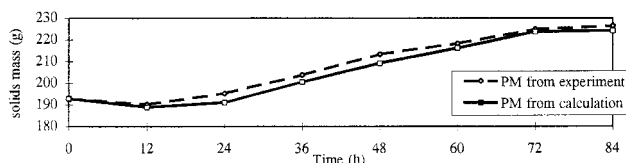
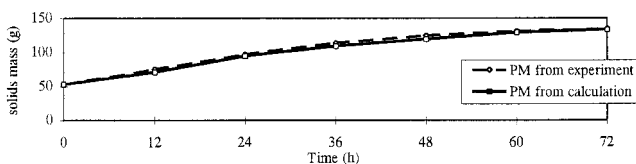
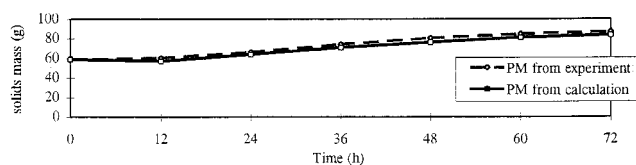
Manufacturer	Local
Al ₂ O ₃ (min)	6.5%
Fe (max)	0.1 mg/g
Mn (max)	50 mg/g
Specific gravity	1.265

Table 3 | Properties of the nonionic polymer.

Code	Kurifloc PN-133
Type	Nonionic
Appearance	White granule
Molecular weight	More than 12 million
Viscosity at 0.1% solution	20–40 cps
pH at 0.1% solution	5.5–7.5
pH application range	5.0–8.0
Charge at 0.8% solution	Up to + 5 meq/l

**Figure 2** | Suspended solids (SS) entering and leaving the reactor.

microscope), settling velocity (v_s , by measuring the drop length of pellets and using a stopwatch) and density (by calculation using Stokes' law). Raw and treated waters were also sampled at 6 h intervals for analysis of pH,

a) 5 mg/l of alum plus 0.3 mg/l PE at 9.6 m/h v_{up} and 30–60 NTU influent for Case A1b) 0.1 mg/l PE at 15 m/h v_{up} and 30–60 NTU influent for Case A2c) 18.7 mg/l of alum plus 0.3 mg/l PE at 9.6 m/h v_{up} and 100–240 NTU influent for Case B1d) 0.3 mg/l PE (as coagulant) at 6 m/h v_{up} and 100–240 NTU influent for Case B2**Figure 3** | Typical accumulation of solids (pellet) mass in the reactor with time. (a) 5 mg/l of alum+0.3 mg/l PE at 9.6 m/h v_{up} and 30–60 NTU influent for Case A1. (b) 0.1 mg/l PE (as coagulant) at 15 m/h v_{up} and 30–60 NTU influent for Case A2. (c) 18.7 mg/l of alum+0.3 mg/l PE at 9.6 m/h v_{up} and 100–240 NTU influent for Case B1. (d) 0.3 mg/l PE (as coagulant) at 6 m/h v_{up} and 100–240 NTU influent for Case B2.

alkalinity, SS, turbidity (HACH 2100A turbidimeter) and aluminium (eriochrome cyanine R colorimetric method with Hitachi A 2100 spectrophotometer).

The pellet mass in the reactor was monitored every 12 h throughout the run and the mass balance of solids entering and exiting the pelletiser was also calculated (see Figure 2). In this study, the steady state of the system was considered to be reached either when the difference between the solids masses of A + B and C + D + E approached zero or when the effluent turbidity was relatively constant.

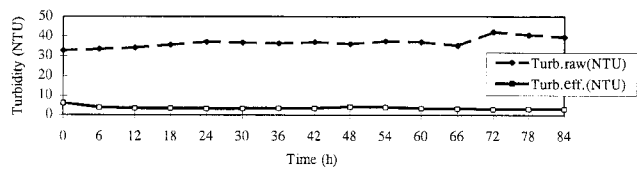
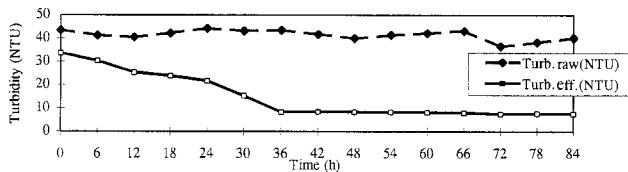
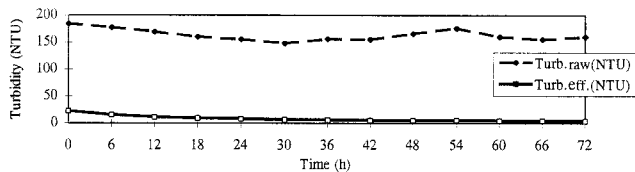
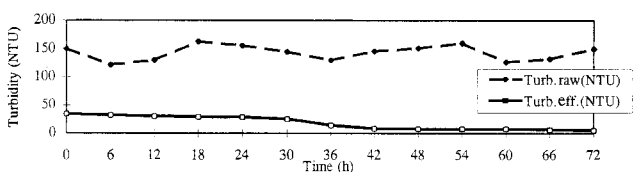
a) 5 mg/l of alum plus 0.3 mg/l PE at 9.6 m/h V_{up} and 30-60 NTU influent for Case A1b) 0.1 mg/l PE at 15 m/h V_{up} and 30-60 NTU influent for Case A2c) 18.7 mg/l of alum plus 0.3 mg/l PE at 9.6 m/h V_{up} and 100-240 NTU influent for Case B1d) 0.3 mg/l PE (as coagulant) at 6 m/h V_{up} and 100-240 NTU influent for Case B2

Figure 4 | Typical profiles of effluent turbidity versus time under different operating conditions. (a) 5 mg/l of alum + 0.3 mg/l PE at 9.6 m/h V_{up} and 30–60 NTU influent for Case A1. (b) 0.1 mg/l PE at 15 m/h V_{up} and 30–60 NTU influent for Case A2. (c) 18.7 mg/l of alum plus 0.3 mg/l PE at 9.6 m/h V_{up} and 100–240 NTU influent for Case B1. (d) 0.3 mg/l PE (as coagulant) at 6 m/h V_{up} and 100–240 NTU influent for Case B2.

RESULTS AND DISCUSSION

Owing to the nature of low turbidity in the feed water, one might anticipate problems in maintaining a sufficient pellet mass in the reactor after the start-up stage, i.e. solids loss in the pellet drain (to keep the pellet height at a pre-determined level of 1,300 mm) could be greater than the amount of solids entering the system (from the raw water and the addition of chemicals). However, the opposite effect is indicated in Figure 3, which shows the typical graphs of solids (or pellet) mass accumulated in the pelletiser. More pellet mass was evidently accumulated in the reactor

Table 4 | Time required to achieve a constant effluent turbidity (t_c) (h).

Cases	Upflow velocity (m/h)		
	6	9.6	15
(A) 30–60 NTU, summer season			
(A1) alum (mg/l) + 0.3 mg/l PE			
3	—	36	30
5	—	18	6
7	—	24	18
10	—	18	18
(A2) nonionic polymer (mg/l)			
0.1	—	48	36
0.2	—	42	42
0.3	—	48	42
(B) 100–240 NTU, rainy season			
(B1) alum (mg/l) + 0.3 mg/l PE			
18.7	8	30	—
21.1	6	30	—
23.4	12	42	—
25.8	12	42	—
(B2) nonionic polymer (mg/l)			
0.1	42	48	—
0.2	42	42	—
0.3	42	48	—

Note: With alum, the resulting water turbidity was always lower than the requirement of 5 NTU of BMWA, whereas that produced with the polymer as the coagulant did not meet this standard.

with time, and about 50–70 h were required before the steady state regarding the constant mass of pellets was reached. It is noted that due to the different amounts of

Table 5a | Experimental results at the 84th hour of running for Case A (summer, 30–60 NTU).

Cases	pH			Alk (mg/l as CaCO ₃)			NTU			Al (mg/l)	
	RW	RM	eff.	RW	RM	eff.	RW	eff.	%	In	Out
(A1) At 9.6 m/h upflow velocity Alum + 0.3 mg/l nonionic polymer											
3	7.6	7.77	7.85	124.3	120.7	118.7	45	7	84	70	144
5	7.6	7.76	7.86	122.5	119.5	118.2	42	2.5	94	73	153
7	7.6	7.75	7.84	124.3	120.9	119.6	45	2.7	94	78	174
10	7.6	7.76	7.85	122.5	118	116.3	42	2.4	94	73	186
At 15 m/h upflow velocity											
3	7.63	7.74	7.81	119.4	117.4	115.2	46	6.6	86	74	95
5	7.62	7.76	7.82	123.1	120.7	118.7	37	3.5	91	70	104
7	7.62	7.75	7.84	123.1	119.6	117.6	37	3	92	70	112
10	7.65	7.77	7.83	121.9	117.8	116	41	2.4	94	70	119
(A2) At 9.6 m/h upflow velocity Polymer (mg/l)											
0.1	7.61	—	7.75	124.3	—	121.9	45	10.5	76	78	80
0.2	7.63	—	7.78	123.1	—	121.9	46	8	83	74	75
0.3	7.63	—	7.77	119.4	—	117	46	7.6	83	74	77
At 15 m/h upflow velocity											
0.1	7.65	—	7.8	122.5	—	121.2	42	7.9	81	72	80
0.2	7.62	—	7.81	119.4	—	117.6	37	8.4	77	70	75
0.3	7.6	—	7.83	121.9	—	120.8	41	7.6	82	70	77

kaolin used, the initial pellet mass built up in the reactor during the start-up process varied for the summer and rainy season scenarios, i.e. more mass was developed in the former case than in the latter (approximately 195 vs 55 g). From the calculation of the mass balance, it was found also that the main contribution (approximately 70–99%) to the solids entering the system was from the influent suspended

solids rather than from the addition of the coagulant and coagulant aid.

Steady state condition

The steady state of the system can be determined based on either the mass balance of pellets in the reactor as earlier

Table 5b | Experimental results at the 72nd hour of running for Case B (rainy season, 100–200 NTU).

Cases	pH			Alk (mg/l as CaCO ₃)			NTU			Al (g/l)	
	RW	RM	eff.	RW	RM	eff.	RW	eff.	%	In	Out
(B1) At 6 m/h upflow velocity Alum + 0.3 mg/l nonionic polymer											
18.7	7.62	7.76	7.79	69.6	57.8	53.6	99	3.9	96.1	78	115
21.1	7.58	7.72	7.8	78.7	69	63.4	132	4.1	96.9	75	133
23.4	7.62	7.69	7.79	72.4	55	50.8	106	4	96.2	77	149
25.8	7.68	7.74	7.83	79.4	66.4	63.4	178	3.5	98.1	80	168
At 9.6 m/h upflow velocity											
18.7	7.67	7.84	7.84	73.8	61.3	58.5	163	4.9	97	70	144
21.1	7.66	7.79	7.84	71.7	61.3	57.1	154	4.5	97	73	153
23.4	7.65	7.8	7.84	80.8	73.8	69	185	4.2	98	78	174
25.8	7.66	7.81	7.86	80.8	69.7	65.5	185	3.7	98	73	186
(B2) At 6 m/h upflow velocity Polymer (mg/l)											
0.1	7.66	—	7.78	71.7	—	71	180	10.4	94	80	85
0.2	7.66	—	7.8	71.7	—	70.4	193	8.2	96	83	87
0.3	7.63	—	7.8	80.8	—	78.6	143	7.1	95	77	80
At 9.6 m/h upflow velocity											
0.1	7.66	—	7.78	71.7	—	67.5	180	18.2	90	79	85
0.2	7.66	—	7.81	71.7	—	68.2	193	8.3	96	74	82
0.3	7.63	—	7.79	80.8	—	76.6	143	9	94	78	88

Note: RW=raw water average value; RM=average value after rapid mixing tank; eff.=effluent water.

stated or the constant treated effluent. Figure 4 illustrates the typical profiles of the effluent turbidity versus time under different operating conditions. With alum as the coagulant and nonionic polymer as the coagulant aid, it took about 6–12 and 18–42 h for the cases of 6 and 9.6 m/h upflow velocities, respectively, before the effluent

turbidity became relatively constant (t_c). On the other hand, Table 4 shows that the process using the Kurifloc PN-133 nonionic polymer as the coagulant required a greater t_c than the alum counterpart. The t_c was at least 36–48 h and the process did not even produce a good effluent quality (discussed below). The poor performance

Table 6a | Characteristics of pellets, pellet mass loading (PML) and pellet retention time (PRT) at the 84th hour of running for Case A (summer, 30–60 NTU).

Cases	Pellet mass (g)	PML				PRT (day)	Pellet*		
		1	2	3	4		<i>d</i> (mm)	<i>v_s</i> (m/h)	ρ (g/cm ³)
(A1) At 9.6 m/h upflow velocity									
Alum + 0.3 mg/l nonionic polymer									
3	220	0.14	0.13	0.2	0.17	6.31	0.21	9.63	1.1
5	226	0.13	0.13	0.18	0.17	11.29	0.21	9.63	1.1
7	234	0.14	0.14	0.19	0.18	7.26	0.22	9.63	1.09
10	237	0.14	0.14	0.17	0.16	11.9	0.22	9.66	1.09
At 15 m/h upflow velocity									
3	238	0.19	0.19	0.19	0.17	4.74	0.2	15	1.17
5	250	0.18	0.18	0.15	0.13	4.36	0.21	15.16	1.16
7	234	0.2	0.2	0.16	0.14	6.22	0.21	15.06	1.16
10	269	0.21	0.21	0.15	0.14	5.56	0.22	15.12	1.14
(A2) At 9.6 m/h upflow velocity									
Polymer (mg/l)									
0.1	233	0.13	0.11	0.19	0.15	7.13	0.18	9.54	1.14
0.2	245	0.12	0.11	0.19	0.15	11.87	0.19	9.6	1.12
0.3	272	0.1	0.1	0.17	0.14	9.02	0.19	9.63	1.12
At 15 m/h upflow velocity									
0.1	226	0.19	0.17	0.18	0.15	5.88	0.18	15	1.21
0.2	212	0.19	0.18	0.17	0.13	5.25	0.18	15	1.21
0.3	265	0.18	0.16	0.15	0.13	4.78	0.19	15	1.19

of the process was obvious from the start, especially for the low NTU feed water (Figure 4b).

From Figure 4, it is apparent that a selection process for pellets of optimum size and density occurred in the reactor; i.e. at the initial stage, and especially with the application of polymer only (Cases A2 and B2 in Figure 4b and 4d), good pellets were not yet completely formed, resulting in the

washout of some 'bad' (small or light) pellets and higher effluent NTU. Only those pellets with settling properties above the upward push could survive, and they subsequently became a nucleus or contact target for one-by-one attachment of destabilised particles to trap or filter out the incoming destabilised colloids, and therefore grew subsequently both in diameter and density. These larger and

Table 6b | Characteristics of pellets, pellet mass loading (PML) and pellet retention time (PRT) at the 72nd hour of running for Case B (rainy season, 100–200 NTU).

Cases	Pellet mass (g)	PML				PRT (day)	Pellet		
		1	2	3	4		d (mm)	v _s (m/h)	ρ (g/cm ³)
(B1) At 6 m/h upflow velocity Alum + 0.3 mg/l nonionic polymer									
18.7	106	0.4	0.4	0.94	0.9	3	0.22	6.21	1.06
21.1	120	0.45	0.44	1.09	1.06	3.28	0.22	6.21	1.06
23.4	103	0.45	0.45	1.02	0.98	3.74	0.23	6.24	1.05
25.8	155	0.45	0.45	1.15	1.13	2.1	0.23	6.24	1.05
At 9.6 m/h upflow velocity									
18.7	135	0.67	0.66	1.21	1.18	1.34	0.21	9.66	1.11
21.1	133	0.69	0.68	1.16	1.13	1.6	0.22	9.69	1.09
23.4	160	0.68	0.67	1.16	1.13	1.55	0.22	9.75	1.09
25.8	157	0.76	0.75	1.18	1.16	1.49	0.23	9.75	1.08
(B2) At 6 m/h upflow velocity Polymer (mg/l)									
0.1	96	0.6	0.56	1.87	1.76	2.93	0.2	6.18	1.07
0.2	95	0.6	0.56	2.02	1.94	3.01	0.2	6.24	1.07
0.3	87	0.52	0.46	1.65	1.57	3.13	0.21	6.24	1.06
At 9.6 m/h upflow velocity									
0.1	125	0.7	0.59	1.44	1.29	2.04	0.19	9.6	1.12
0.2	132	0.72	0.62	1.46	1.4	2.04	0.2	9.63	1.11
0.3	102	0.67	0.58	1.4	1.32	2.28	0.21	9.66	1.1

Note: PML (1) = $\frac{\text{g SS applied to the system/day}}{\text{g pellet mass in reactor}}$

or: day⁻¹;

(2) = $\frac{\text{g SS removed by the system/day}}{\text{g pellet mass in reactor}}$

or: day⁻¹.

(3) = average NTU fed to the system/g pellet mass in reactor.

(4) = average NTU removed by the system/g pellet mass in reactor.

PRT = pellet retention time = PM in reactor (g)/PM discharged (g/d) (including those sampled for lab analysis) or days.

d = pellet diameter, mm.

v_s = settling velocity, m/h.

ρ = pellet density, g/cc.

*Taken from the top layer (or 1300 mm height) of the pellet blanket.

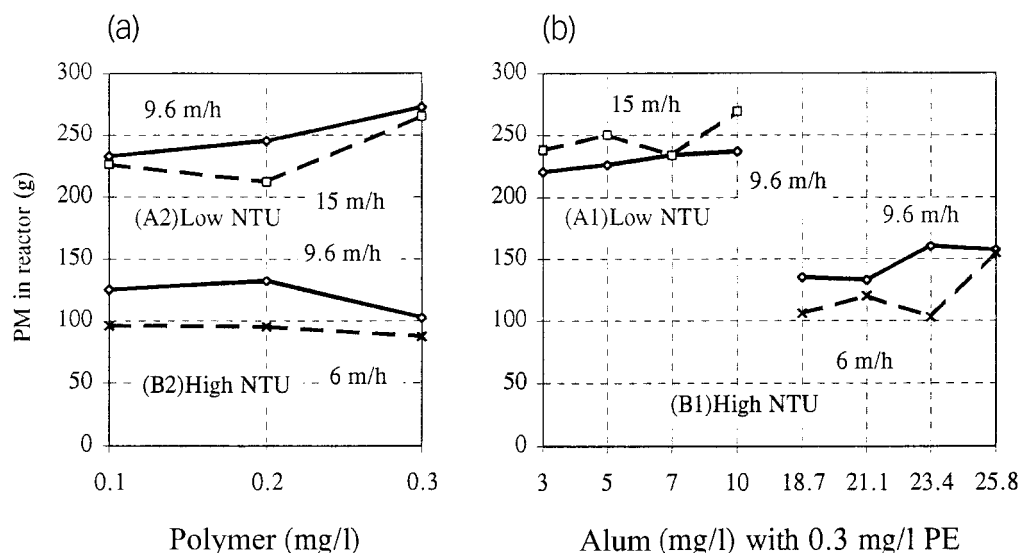


Figure 5 | Pellet mass (PM) in the reactor at steady state under different operating conditions.

heavier pellets then accumulated in the reactor and made the effluent clearer and clearer with time. More pellet mass was also observed during this period.

In the case of alum as the coagulant, the time t_c was shorter, especially at low upflow velocity (6 m/h) and relatively high alum dose (see Case B1 in Table 4). The probable explanation of this result is greater destabilisation due to the high dose of alum (18–25 mg/l) in conjunction with the bridging power of the polymer. With the same upflow velocity of 9.6 m/h but under the different operating conditions of Cases A1 and B1, i.e. a low alum dose (3–10 mg/l) for low feed turbidity (30–60 NTU) versus a high dose (18.7–25.8 mg/l) for high feed turbidity (100–240 NTU), the critical time t_c was somewhat lower for the first case. The higher initial pellet mass as well as the lower removal efficiency requirement (lower input NTU but with the same output requirement of 5 NTU) are the possible justifications of this finding.

Process performance

The average results of the experiments are given in Table 5a and 5b. The pH values of the raw water before and after rapid mixing, and of the effluent were not very different,

i.e. in the range of 7.58–7.67, 7.69–7.84 and 7.75–7.86, respectively. The corresponding alkalinity did not differ much either; a lower alkalinity value of about 70–80 mg/l as CaCO_3 was found in the rainy season, compared with 120–125 mg/l as CaCO_3 in summer. This alkalinity dropped only slightly (1–5 mg/l) when the polymer (Cases A2, B2) or a low alum dose (Case A1) was used for the coagulation. The higher degree of alkalinity reduction (11–20 mg/l) was found in the scenario of high alum dose together with low alkalinity in raw water. It is noted that in all A1 and B1 cases, regardless of upflow velocity, where alum was used as the coagulant and the polymer as the coagulant aid, the turbidity of the product water was always lower than the standard of 5 NTU set by the BMWA, and the better effluent quality was evident when a higher dose of alum was used. For Cases A1 and B1, this corresponds to the Al/T (aluminium : turbidity) ratio of 0.004–0.015 and 0.014–0.022 g/g SS, respectively, and the P/T (polymer : turbidity) ratio of 0.0054–0.0059 and 0.0020–0.0030 g/g SS, respectively, which is higher than those reported by Tambo & Matsui (1987, 1989) and Tambo & Watanabe (1978). This is because of the great difference between the NTU in the influent of this study (as low as 30 NTU) and other studies (as high as 3,000 mg/l SS).

In Cases A2 and B2 where only 0.1–0.3 mg/l Kurifloc PN-133 polymer was used as the coagulant, a very good effluent quality was never achieved; i.e. 7.6–10.5 and 7.1–18.2 NTU for the feed water of 30–60 and 100–200 NTU, respectively. A lower NTU was however probably still possible with a dose of the polyelectrolyte higher than 0.3 mg/l. The corresponding P/T ratio was 0.0019–0.0053 and 0.0006–0.0023 g/g for Cases A2 and B2, respectively. Despite the fact that the polymer alone could develop a satisfactory pellet mass in the reactor (Figure 3) the destabilisation capability of the polyelectrolyte at the specified doses was not sufficient to produce a good result in terms of product water quality. The advantage of this process was, however, its low sludge yield. As a result, in cases where low sludge (pellet) production and/or minimal aluminium content in the product water is required (see below), the polymer as the coagulant, but at a higher dosage than 0.3 mg/l, may be the only choice to achieve a clearer effluent.

The drinking water standard for aluminium is set by the WHO at 200 $\mu\text{g/l}$. In this study, although the Al content in the product water increased with the alum dose it was lower than 186 $\mu\text{g/l}$ in all cases. When a lower dose of 3–10 mg/l alum was used for the low NTU waters, only about 95–120 $\mu\text{g/l}$ of Al was detected in the effluent. But when the alum was not used in the coagulation process, the value dwindled to about 75–88 $\mu\text{g/l}$, roughly equal to the influent Al content.

Pellet mass

The characteristics of the pellets formed in the pelletiser under different operating conditions are shown in Table 6a and b and Figure 5. More pellet mass (PM) was detected in the low NTU cases, A1 and A2, than that in the high NTU scenarios B1 and B2; this is due to the different startups which in turn resulted in different initial pellet masses, i.e. about 188–234 and 53–75 g for the low and high NTU cases, A and B, respectively. In practice, where the process will be run continuously for a long period, the pellet mass for cases of the same influent turbidity should eventually become similar.

The pellet mass loading (PML) expressed in different units (see Table 6) was suggested as the criterion for

optimum operating of the process. In the first two scenarios, the suspended solids applied or removed in g/d were compared with the pellet mass (PM, g) in the system. For the application of the first unit, if the incoming SS expressed as g/d is known, the PM required to exist in the reactor can then be computed and targeted for. However, if only the suspended solids to be removed by the system are to be taken into account, the second expression can be used instead. For the last two units, the application is similar; the only difference is to use the NTU value in place of the SS number. For Case B or in the rainy season, the PML using alum and polymer as the coagulant and coagulant aid, respectively, was shown to be in the range of 0.4–0.76 day^{-1} whereas that for Case A (30–60 NTU) was 0.13–0.21 day^{-1} . The corresponding values expressed as NTU/g PM were 0.90–1.21 and 0.16–0.20, respectively. It is noted that the PM loading expressed by NTU under the 100–200 NTU scenario of Case B1 was about twice that with the SS expression. The numbers for these two criteria at the low turbidity of 30–60 NTU were nevertheless quite similar. This finding may be attributed to the higher NTU to SS ratio of the raw water at the low SS condition. A similar conclusion may be drawn for the scenario using the polymer as the sole coagulant, i.e. with 0.1–0.19 and 0.46–0.72 day^{-1} , and 0.13–0.19 and 1.3–2.0 NTU/g PM for Cases A2 and B2, respectively. Again, it should be borne in mind that with the application of the polymer at these doses as the coagulant, the effluent turbidity was not very good and could only go down to about 8 or 10 NTU. A conclusion on the optimum PML could not be fully drawn from this preliminary study. However, if a lower initial PM is targeted for lower operating costs, it can be concluded that as high as 0.76 day^{-1} of PML is possible for a good effluent quality of lower than 5 NTU. The PML, as a design criterion, should be developed from a long-term study with a larger pilot plant and with water from different sources.

Another criterion suggested to be used as an indicator of the performance of the system was the Pellet Retention Time or PRT (in days) which can be calculated as shown in Table 6. When the alum was used as the coagulant, the PRT was found to be in the range of 1.3 to 12 days, depending on the initial PM after the start-up process.

The corresponding numbers for the cases using the polymer as a coagulant were 3 to 12 days. It is noted that this was possibly the first work done on the pelletiser for turbidity removal with actual low-NTU real river water and it is also the first time these two criteria, i.e., PML and PRT, were suggested as process performance indices. Precise values for the said parameters cannot readily be suggested now and more work on the fine tuning is recommended.

It is apparent from Table 6, which shows the characteristics of the pellets taken from the top level of the pellet blanket, that the diameters of the pellets formed in the cases using alum as a coagulant were only about 0.20 to 0.22 mm, probably due to the low turbidity in the feed water when compared with work performed by others. However, with the selection mechanisms acting due to various upflow velocities, the pellet density (calculated from Stokes' law) increased from 1.05–1.06 to 1.08–1.11 and 1.14–1.17 for the 6, 9.6 and 15 m/h scenarios, respectively. For the polymer-as-coagulant conditions, the related numbers were 0.18–0.21 mm in diameter, and 1.06–1.07, 1.10–1.14 and 1.19–1.21 for those three upflow velocities, respectively. The pellet diameters reported here are much lower than those found by Tambo & Watanabe (1978) (0.2–4 mm), Tambo & Matsui (1987) (0.9–2 mm), and Tambo & Matsui (1989) (0.7–2 mm), possibly because of: (a) the low NTU used in this study; (b) river water used in this study, with different characteristics from the synthetic water used by others; and (c) different heights from which pellets were taken for analysis (i.e. only from the top or a critical layer in this study versus all levels in other investigations). The density of the pellets formed in this experiment was in the range reported by others, i.e. 1.06–1.12 g/cm³ versus approximately 1.002 to 1.10 (Tambo & Watanabe 1978) and 1.08–1.25 (Tambo & Matsui 1987, 1989).

CONCLUSIONS

A pelletiser process was successfully and satisfactorily used for turbidity removal from a low NTU feed water taken from a local river, the Chao Phraya. The key was the

start-up process which was undertaken with 3,000 mg/l kaolin and a dose of alum and a polymer. Even with low turbidity in the influent, the pellet mass in the reactor increased with time until a steady state was reached after about 50–70 h. With a low initial pellet mass (PM), 'highly' turbid water in the rainy season of 100–200 NTU and an upflow velocity of 9.6 m/h, the process proved capable of producing an effluent with quality better than the 5 NTU requirement of the Bangkok Metropolitan Waterworks Authority. The corresponding Al/T and P/T ratios were 0.004–0.022 and 0.0030–0.0054 g/g SS, respectively. However, when only a nonionic polymer was used as the coagulant, with a P/T ratio of 0.0006 to 0.0053 g/g SS, the product water was not of high quality and the NTU ranged from 7 to 18. Thus a higher chemical dose needs to be used if a better effluent quality is required. With the lower alum dose used in this study than in regular water plants, the product water had a low concentration of aluminium, i.e. 75–186 µg/l, which is lower than the 200 µg/l standard established by the WHO. Two new parameters, i.e. PML (pellet mass loading) and PRT (pellet retention time or pellet age, θ_c) were suggested as criteria to determine the process performance. A PML as high as 0.76 day⁻¹ and a PRT as low as 1.3 day were shown to be effective for turbidity removal for this low NTU feed river water. More work is needed to determine the optimum value of these suggested parameters.

ACKNOWLEDGEMENTS

This study was supported by the Thailand Research Fund.

REFERENCES

- Bratby, J. 1980 *Coagulation and Flocculation*. Upland Press, London, pp. 54–89.
- O'Melia, C. R. 1972 In: *Coagulation and Flocculation: Physicochemical Process for Water Quality Control* (W. J. Weber Jr, ed.). Wiley Interscience, New York.

- Panswad, T. & Channarong, B. 1998 Turbidity removal by the up-flow pelletisation process for low turbidity water. *J. Wat. Supply: Res. Technol.—AQUA*. **47**(1) 36–40.
- Panswad, T. & Polwanich, S. 1998 Pilot plant application of pelletisation process on low turbidity river waters. *J. Wat. Supply: Res. Technol.—AQUA*. **47**(5) 1–9.
- Suzuki, T., Tambo, N. & Ozawa, G. 1993 A new sewage treatment system with fluidised pellet bed separator. *Wat. Sci. Tech.* **27**(11), 185–192.
- Tambo, N. & Matsui, Y. 1987 Metastable state operation for fluidised bed pellet separation. *Proceedings of the 6th IWSA Asia-Pacific Regional Conference*, Bangkok, pp. 397–404.
- Tambo, N. & Matsui, Y. 1989 Performance of fluidised pellet bed separator for high-concentration suspension removal. *J. Wat. Supply: Res. Technol.—AQUA*. **38**(1), 16–22.
- Tambo, N. & Wang, X. C. 1993a The mechanism of pellet flocculation in a fluidised pellet bed operation. *J. Wat. Supply: Res. Technol.—AQUA*. **42**(2), 67–76.
- Tambo, N. & Wang, X. C. 1993b Control of coagulation condition for treatment of high-turbidity water by fluidised pellet bed separation. *J. Wat. Supply: Res. Technol.—AQUA*. **42**(4), 212–222.
- Tambo, N. & Wang, X. C. 1993c Application of fluidised pellet bed technique in the treatment of highly coloured and turbid water. *J. Wat. Supply: Res. Technol.—AQUA*. **42**(5), 301–309.
- Tambo, N. & Watanabe, Y. 1978 Physical characteristics of floc. 1. The floc density function and aluminium floc. *Wat. Res.* **13**, 409–419.
- Tambo, N., Ozawa, G. & Suzuki, T. 1993 Replacement of the final settling basin by a fluidised pellet bed separator to improve efficiency of activated sludge systems. *Wat. Sci. Technol.* **27**(11), 253–256.
- Tambo, N., Shimizu, T., Kudo, K., Ozawa, G. & Hanaguchi, T. 1994 An anaerobic fluidised pellet bed bioreactor process for simultaneous removal of organic, nitrogenous and phosphorus substances. *Wat. Res.* **28**(9), 1943–1952.
- Wang, X. C. & Tambo, N. 1993 Kinetic study of fluidized pellet bed processes II. Development of a mathematical model. *J. Wat. Supply: Res. Technol.—AQUA*. **42**(3), 155–165.
- Wang, X. C., Tambo, N. & Matsui, Y. 1993 Kinetic study of fluidized pellet bed processes I. Characteristics of particle motion. *J. Wat. Supply: Res. Technol.—AQUA*. **42**(3), 146–154.
- Yusa, M. & Gaudin, A. M. 1964 Formation of pellet-like flocs of kaolinite by polymer chains. *Ceramic Bull.* **43**, 402–406.
- Yusa, M., Suzuki, H. & Tanaka, S. 1975 Separation of liquids from solids by pellet flocculation. *J. Am. Wat. Wks Ass.* **57**, 397–402.