PAMUKKALE ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
PAMUKKALE UNIVERSITY ENGINEERING COLLEGE
MÜHENDİSLİK BİLİMLERİ DERGİSİ
JOURNAL OF ENGINEERING SCIENCES
YIL : 1998
CİLT : 4
SAYI : 1-2
SAYFA : 527-535

EFFECTS OF DESIGN AND OPERATIONAL VARIABLES ON FILTRATE QUALITY OF SLOW SAND FILTERS

Mehmet Emin AYDIN
Selçuk University, Engineering Faculty, Environmental Engineering Department, Konya

ABSTRACT

This experimental research was carried out to determine the effects of design and operational parameters on filtrate quality of slow rate sand filters. Three slow sand filters containing sand of different effective sizes (170, 360 and 450 mm) were operated at treatment rates ranging from 100 to 500 mm/h at three temperatures of 25 ^oC, 15 ^oC and 5 ^oC. High percentage removal of coliform bacteria, suspended solids, and turbidity was achieved throughout the investigation. An improved removal of suspended solids with increasing sand grain size was recorded. With increasing flow rates some reduction in the removal of coliforms were observed. Ammonia, TOC and dissolved oxygen contents of influent and the filtrates were also measured. Overall ammonia removal was declined with decreasing temperature and increasing flow rate. TOC removal of overall 0.7 mg/l corresponds about to the reduction in the dissolved oxygen content. By looking at the oxygen consumption, there is no evidence to suggest that nitrification took place in the filters. Thus, the removal of ammonia must be due to the anabolic uptake.

Key Words : Slow sand filters, Sand size, Bed depth, Rates of filtration, Temperature

YAVAŞ KUM FİLTRELERİNDE TASARIM VE ÇALIŞMA DEĞİŞKENLERİNİN ÇIKIŞ KALİTESİNE ETKİLERİ

ÖZET

Tasarım ve çalışma parametrelerinin filtre çıkış suyu kalitesi üzerindeki etkilerinin araştırılması amacıyla değişik etkin dane çaplarında (170, 360 ve 450 mm) kuma sahip üç tane yavaş kum filtresi 100 mm/h den 500 mm/h'e kadar değişen filtrasyon hızlarında ve 25 ^oC, 15 ^oC ve 5 ^oC olmak üzere üç değişik sıcaklıkta çalıştırılmıştır. Araştırma boyunca yüksek koliform bakteri, askıdaki katı maddeler ve bulanıklık giderimine ulaşılmıştır. Kum danesi etkin çapındaki artışla, askıdaki katı maddelerin gideriminde iyileşme olurken artan filtrasyon hızıyla koliform bakteri gideriminde azalma olduğu gözlenmiştir. Filtrelerin giriş ve çıkışında Amonyak, Toplam Organik Karbon (TOK) ve Çözünmüş Oksijen miktarları da ölçülmüştür. Araştırma boyunca azalan çalışma sıcaklığıyla ve artan filtrasyon hızlarıyla amonyak gideriminin azaldığı gözlenmiştir. Toplam organik karbon giderimi ortalama 0.7 mg/l olarak bulunmuştur. Bu TOK giderim değeri yaklaşık olarak filtre yatağı boyunca ortalama olarak kullanılan çözünmüş oksijen miktarına karşılık gelmektedir. Oksijen tüketimine bakılırsa filtrelerde nitrifikasyon olduğu söylenemez, dolayısıyla amonyak giderimi anaboliktir.

Anahtar Kelimeler : Yavaş kum filtreleri, Dane çapı, Yatak derinliği, Filtrasyon hızı, Sıcaklık

1. INTRODUCTION

In the design and operation of slow sand filters the principal variables to be considered are depth of sand bed, size of the sand grains, rate of application of the raw water and temperature of operation. Investigations have been carried out to link some of these factors but no systematic research has been done to investigate the effect of all parameters. Therefore this experimental research has been carried out to determine the effect of design and operational parameters on filtrate quality.

The minimum depth of sand before re-sanding is variously reported Cox (1969) suggested a conservative minimum sand depth of 800 mm while Ridley (1967) put forward 650 mm. London filters have been reported as operating to a minimum depth of only 300 mm (Toms and Bayley, 1988). This low figure of 300 mm would appear to be adequate for the removal of turbidity from water (Ellis and Aydın, 1993) and will also be sufficient for the removal of a high percentage of coliform from a good quality feed water but for the removal of viruses and for the oxidation of ammonia the greater minimum depth of 600 mm would be essential (Windle-Taylor, 1974; Ellis and Aydın, 1993). The regression models developed by Ellis and Aydın (1995) concerned with the extension of biological activity and the penetration of solids into the sand bed demonstrated that the most active part of the filter beds was the first 400 mm depth.

Limited agreement has been noticeable about the preferred effective size (ES) of the sand grains recommended by various authors. Toms and Bayley (1988) suggested an ES of about 320 mm. Cox (1969) proposed between 200 and 400 mm while Ridley (1967) indicated the necessity for an ES of between 250 and 350 mm. Thanh and co-workers (1983) and also Huisman and Wood (1974) recommended between 150 and 350 mm.

The rates of treatment reported for non-pretreated raw waters by slow sand filters varies between about 0.08 m/h to about 0.21 m/h. A “conventional rate” for treatment is often suggested as being 0.1 m/h (Van Dijk and Oomen, 1978). A range of treatment rates from as low as 0.05 m/h up to 0.15 m/h has been suggested by Ridley (1967) although for the higher rates of treatment he considered that pre-treatment of the feed water would be required. The Metropolitan Water Board, London (Windle-Taylor, 1969/70), as a result of laboratory-scale investigations, reported that rates of treatment of as high as 500 mm/h could be applied with no appreciable deterioration of the quality of the filtrate produced. Reports of Joshi et al., (1982) indicated that treatment rates of as high as 300 mm/h are acceptable but only with good quality feed water. Average treatment rates of 320 mm/h have been reported for the operation of full scale London slow sand filters (Rachwal et al., 1988) although it was suggested that pre-treatment of the applied water would nearly certainly be required at such high rates. Rachwal and co-workers (1988) reported an inverse relationship for full scale filters between rates of treatment and run length (i. e. period between two consecutive cleanings) so that the cumulative volume filtered per run for either high rate or conventional rate was essentially the same. Williams (1987) and Kerkhoven (1979) reported on operation of slow filters at rates of 50 and 100 mm/h and 200 and 300 mm/h respectively. Ellis and Aydın (1993) investigated the effect of filtration rate by operating laboratory scale filters at filtration rates between 100 and 500 mm/h. They found no significant deterioration in the quality of the filtrate with increasing rate of treatment although run lengths declined at the faster rates. Williams (1987), using three fine-grain filters (ES 260 mm) and one coarser grained filter (ES 620 mm) at treatment rates of 50 mm/h and 100 mm/h, achieved a 2.3 log removal of fecal coliforms with the finer grain filters and the slightly lesser figure of 2.0 log with the coarser grained filter. The later investigations with a flow rate of 200 mm/h were abandoned as a result of the too frequent blocking of the filters.

2. EXPERIMENTAL

Three laboratory scale slow sand filters were operated in continuos flow mode at the laboratories over a period of 24 months. Following an initial maturation period of 3 months the remaining time was devided equally between three separate temperature periods of 25^{o}C, 15^{o}C and 5^{o}C. During each of these temperature periods five distinct rates of treatment were operated (100, 200, 300, 400 and 500 mm/h) Each filter (Figure 1), constructed of transparent perspex tubing, was of 150 mm internal diameter, with a sand depth of 1.2 m and with a constant head of 1.5 m of water above the sand surface. The effective sizes of the sand were 170 mm in filter A, 350 mm in filter B, and 450 mm in filter C. The corresponding uniformity coefficients were 1.6, 1.4 and 1.4 respectively. Each filter column had a flanged joint above the sand surface, to facilitate

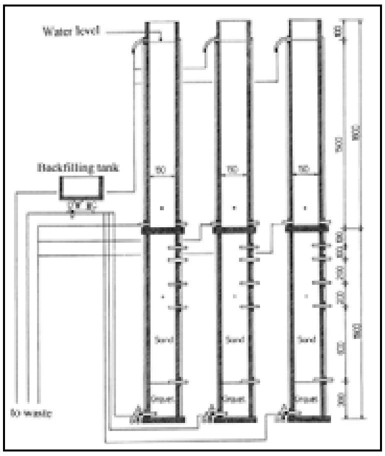

Figure 1. Laboratory scale filters used during the investigation

cleaning. Each filter was equipped with a valve for the rapid removal of the supernatant water from above the sand level. Each filter was designed to permit the filling and re-filling of the filter bed with water from the bottom. In order to be able to maintain a constant temperature within the filter columns it was necessary to insulate them with glass-fiber jackets. Each sand bed was cleaned when it was no longer possible to pass the required flow of water at the maximum head (1.5 m) available. This cleaning was achieved by rapidly running-off the supernatant water from the reservoir, uncoupling the filter column at the flanged joint and carefully scraping off between 30 and 70 mm of the surface sand. An amount of clean sand, identical to the removed, was then replaced at the sand surface and the filter re-assembled and re-filled.

Feed water for the filters was abstracted from a stream. On occasions settled sewage was added to the abstracted stream-water to maintain the count of total coliform organisms at about 4000/100 ml. Spot samples from feed water and from the various filtrates were taken three times a week. Feed and filtrate samples were analyzed for total coliform bacteria, fecal coliforms, suspended solids, turbidity, pH, nitrate nitrogen, ammoniacal nitrogen and total organic carbon (TOC). All the analyses except nitrogen were carried out as described in standard methods for the examination of water and wastewater (APHA, AWWA, WPCF, 1989). The total coliforms and fecal coliform organisms were determined by a membrane filtration technique (0.45 mm) with the total coliforms being developed on a BBL M-Endo broth at 37 ^{o}C for 24 hours and the fecal coliforms on a Difco mFc broth at 44.5 ^{o}C for 24 hours. Turbidities were determined using a Hach Turbidimeter (model 16800) and the nitrates and ammonias by a Palin test photometric method. Nitrogen analyses were also tried initially with distilation method as described in standard methods but due to the nitrogen concentrations beeing too low for distillation method Palin test Photometric method was prefered. Palin test method is developed for low concentration nitrogen containing potable water samples. The Palin test ammonia determination relies upon an indophenol technique with the developed colour being measured at 640 nm. The nitrate determination follows a reduction to nitrite and the colour from the ensuing diazonium reaction is measured at 570 nm.

Dissolved-oxygen measurements were carried out both to determine the D.O. content of the water immediately above the sand bed and in the filtrates from all three filters. To sample the filtrate water for D.O. determinations the abstracted water was passed immediately by tube into the bottom of a BOD bottle containing a small quantity of light oil to prevent re-oxygenation of the water during the slow filling of the bottle.

3. RESULTS AND DISCUSSION

Over the whole of the investigation it was seen that the quality of the feed water to the three filters varied considerably. The fecal coliform counts varied between 12750 per 100 ml to as little as 10/100 ml with a mean of 1143. For the total coliforms the corresponding figures were 40500, 10 and 4605. Suspended solids varied from 31.8 mg/l to 0.9 mg/l with a mean of 6.3, with 37, 0.7 and 6.1 NTU being the equivalent figures for the turbidity.

All the data obtained for the filtrates from the three filters together with their removal efficiencies are summarized in Tables 1 to 4. These tables include the results for the five filtration rates at each of the three temperatures.

Table 1. Removal of Suspended Solids

Application Flow Rate (mm/h)-Filter	25 ^{o}C Period Mean Content (mg/l)		Log Removal	15 ^{o}C Period Mean Content (mg/l)		Log Removal	5 ^{o}C Period Mean Content (mg/l)		Log Removal
	Inflow	Filtrate		Inflow	Filtrate		Inflow	Filtrate	
100 A	13.60	0.35	1.59	2.42	0.32	0.880	2.70	0.30	0.970
100 B	13.60	0.31	1.64	2.42	0.21	1.062	2.70	0.20	1.030
100 C	13.60	0.23	1.77	2.42	0.24	1.004	2.70	0.20	1.030
200 A	9.75	0.71	1.14	10.6	0.31	1.534	3.90	0.30	1.110
200 B	9.75	0.62	1.20	10.6	0.44	1.563	3.90	0.40	0.989
200 C	9.75	0.47	1.32	10.6	0.33	1.507	3.90	0.30	1.110
300 A	8.99	0.45	1.30	6.60	0.45	1.166	2.70	0.50	0.732
300 B	8.99	0.44	1.31	6.60	0.29	1.357	2.70	0.50	0.732
300 C	8.99	0.33	1.44	6.60	0.28	1.372	2.70	0.50	0.732
400 A	4.68	0.58	0.91	7.50	0.33	1.357	2.20	0.40	0.740
400 B	4.68	0.48	0.99	7.50	0.30	1.398	2.20	0.50	0.643
400 C	4.68	0.45	1.02	7.50	0.24	1.495	2.20	0.60	0.564
500 A	4.39	0.63	0.84	2.50	0.35	0.854	2.30	0.50	0.663
500 B	4.39	0.76	0.76	2.50	0.41	0.785	2.30	0.70	0.517
500 C	4.39	0.43	1.01	2.50	0.26	0.983	2.30	0.60	0.583

Log Removal = Log_{10} (Inflow Content) - Log_{10} (Filtrate Content)

3. 1. Suspended Solids and Turbidity Removal

At all three temperatures investigated an initial observation of the results (Table 1) seemed to indicate that there had been a general, decline in the removal of suspended solids with all the filters as the flow rates had been increased. This decline in removal efficiencies with increasing flow rates was, however, more definite at the highest temperature (25°C) than at the two lower temperatures. This more definite correlation was demonstrated by the appreciable correlation coefficients of 0.88 (filter A), 0.94 (filter B) and 0.91 (filter C) obtained for the results for the 25°C period. At 5°C period the correlation coefficients between declining removal rates for suspended solids and increasing flow rates were 0.98 with filter B and 0.90 with filter C.

During the investigation at the highest temperature (25 °C) the lowest removal figure for suspended solids was 0.76 log (filter C, 500 mm/h). With the temperature of 15 °C the removal figures for all three filters were unexpectedly low at the lowest flow rate. This was probably due to the low content of suspended solids in the feed water during that period. Filtrate content of suspended solids is reduced below 1 mg/l generally withouth depending on whether inflow content is low or high. Therefore, the removal rate apears as low when inflow content is low. During the 15 °C investigation there was very little difference demonstrated between the removal rates at 300 mm/h and those for 400 mm/h but there was a marked decline in suspended solids removal with the most rapid (500 mm/h) rate of treatment. Again, during the 5 °C investigation the rate of removal of suspended solids was surprisingly low at the 100 mm/h treatment rate but, apart from that, the removal rate declined from 200 mm/h to 500 mm/h, to a minimum mean of about 0.58 log.

Overall the content of suspended solids in any of the three filtrates did not surpass a mean of 0.76 mg/l for any combination of flow, temperature and sand grain size even for the maximum flow rate used (500 mm/h) at the lowest temperature (5 °C) and with the coarsest sand (450 mm). At the highest temperature investigated (25 °C) the removal of suspended solids nearly consistently improved from the fine filter A to the coarse filter C. This pattern was not so evident at 15 °C although the coarsest filter again produced the lowest content of suspended solids in any of the filtrates; particularly with the higher treatment rates. With the 5 °C period no pattern was evident between the three filters as far as the removal of suspended solids was concerned.

No discernible difference could be detected between the removal of suspended solids by the filters at 25 °C and 15°C although there was an appreciable decline in the proportion of suspended solids removed during the 5 °C investigation. No discernible difference could be detected between the removal of suspended solids by the filters at 25 °C and 15°C although there was an appreciable decline in the proportion of suspended solids removed during the 5 °C investigation.At the 25 °C the pattern of declining removal with increasing flow rate, evident with the suspended solids, was less evident with the turbidity removal (Table 2) and, it was not possible to produce any meaningful correlation between increasing flow rate and the degree of turbidity removal.

Table 2. Removal of Turbidity

Application Flow rate (mm/h)-Filter	25 °C Period Mean Content (NTU)		Log Removal	15 °C Period Mean Content (NTU)		Log Removal	5 °C Period Mean Content (NTU)		Log Removal
	Inflow	Filtrate		Inflow	Filtrate		Inflow	Filtrate	
100 A	18.48	0.34	1.735	1.70	0.23	0.867	2.80	0.22	1.105
100 B	18.48	0.32	1.762	1.70	0.23	0.869	2.80	0.23	1.085
100 C	18.48	0.33	1.747	1.70	0.27	0.799	2.80	0.26	1.032
200 A	8.21	0.50	1.215	7.90	0.26	1.483	4.60	0.30	1.186
200 B	8.21	0.52	1.199	7.90	0.27	1.466	4.60	0.37	1.095
200 C	8.21	0.51	1.207	7.90	0.24	1.517	4.60	0.27	1.231
300 A	9.99	0.32	1.495	3.40	0.26	1.117	2.00	0.21	0.979
300 B	9.99	0.33	1.482	3.40	0.21	1.209	2.00	0.23	0.939
300 C	9.99	0.34	1.469	3.40	0.25	1.134	2.00	0.25	0.870
400 A	4.90	0.23	1.320	6.50	0.23	1.451	2.10	0.26	0.907
400 B	4.90	0.27	1.259	6.50	0.22	1.471	2.10	0.25	0.924
400 C	4.90	0.29	1.228	6.50	0.22	1.471	2.10	0.24	0.942
500 A	4.23	0.29	1.164	2.20	0.22	1.000	1.90	0.22	0.936
500 B	4.23	0.29	1.164	2.20	0.22	1.000	1.90	0.25	0.881
500 C	4.23	0.25	1.228	2.20	0.23	0.981	1.90	0.26	0.864

Log Removal = Log_{10} (Inflow Content) - Log_{10} (Filtrate Content)

Table 3. Removal of Fecal Coliforms

Application Flow Rate (mm/h)-Filter	25 °C Period Mean Content (CFU / 100 ml)		Log Removal	15 °C Period Mean Content (CFU / 100 ml)		Log Removal	5 °C Period Mean Content (CFU / 100 ml)		Log Removal
	Inflow	Filtrate		Inflow	Filtrate		Inflow	Filtrate	
100 A	450	17.3	1.41	753	0.00	Total	808	1.90	2.629
100 B	450	2.50	3.22	753	0.00	Total	808	1.10	2.866
100 C	450	3.30	3.22	753	0.00	Total	808	0.60	3.129
200 A	1950	11.0	3.22	1378	0.20	3.75	517	12.4	1.620
200 B	1950	13.0	3.22	1378	0.70	3.29	517	7.90	1.816
200 C	1950	9.20	3.30	1378	0.00	Total	517	5.10	2.006
300 A	1310	16.9	1.89	1625	0.30	3.83	577	6.30	1.962
300 B	1310	11.0	2.08	1625	5.00	2.51	577	3.70	2.193
300 C	1310	23.0	2.77	1625	1.40	3.07	577	41.3	1.045
400 A	780	15.0	2.72	1348	1.00	3.13	658	33.5	1.293
400 B	780	29.0	1.43	1348	2.90	2.77	658	13.8	1.678
400 C	780	6.00	3.09	1348	1.80	2.87	658	15.0	1.642
500 A	1090	62.0	2.24	793	10.5	1.88	555	24.6	1.353
500 B	1090	41.0	2.42	793	4.70	2.23	555	53.1	1.019
500 C	1090	23.0	2.68	793	4.40	2.26	555	41.1	1.130

Log Removal = Log_{10} (Inflow Content) - Log_{10} (Filtrate Content)

The lowest average removal of turbidity at this temperature was 1.16 log with filters A and B at the rate of 500 mm/h. The pattern of improvement from the fine filter (A) to the coarse filter (C), noticeable with the removal of suspended solids at 25 °C, was not reproduced with the turbidity results. The removal of turbidity for the investigation at 15 °C and 5 °C (Table 2) was obviously related to the turbidity levels in the inflow, with some unusually low figures being produced for the lowest flow rate of 100 mm/h at both temperatures. However, throughout the whole investigation the turbidity levels in the filtrates were invariable less than 0.5 NTU. Therefore when the inflow content is high the removal also appears high whereas when the inflow content is low the removal appears low. However filters perform well under both conditions. No general decline in turbidity removal with increasing flow rate was discernible with the 15 °C results but a decline was noticeable with the 5 °C results. In addition, a general decline in turbidity removal with decreasing temperature was evident.

3. 2. Removal of Coliform Bacteria

With the fecal coliform removal at 25 °C (Table 3) there was some tendency demonstrated towards a reduction in removal efficiency as the flow rates increased, with the coarse filter being generally the most effective and the finest filter being the least effective. There was, however, a noticeable reduction in the number of total removals of fecal coliforms as the rate of flow increased. The removal of the total coliforms (Table 4) generally reflected that of the fecal coliforms although the decline in removal efficiencies with increasing flow was generally more pronounced with the total coliforms as opposed to the fecal coliforms. Again the best results were generally obtained from filter C and again there was a noticeable reduction in the number of complete removals as the rate of flow was increased from 100 mm/h to 500 mm/h.

Table 4. Removal of Total Coliforms

Application Flow Rate (mm/h)-Filter	25 °C Period Mean Content (CFU / 100 ml)		Log Removal	15 °C Period Mean Content (CFU / 100 ml)		Log Removal	5 °C Period Mean Content (CFU / 100 ml)		Log Removal
	Inflow	Filtrate		Inflow	Filtrate		Inflow	Filtrate	
100 A	3210	2.20	3.16	1994	0.00	Total	4853	6.00	2.909
100 B	3210	3.80	2.92	1994	0.30	3.782	4853	4.60	3.023
100 C	3210	2.30	3.16	1994	0.10	4.258	4853	4.00	3.084
200 A	12030	7.00	3.22	3040	1.20	3.404	2280	60.9	1.566
200 B	12030	6.60	3.30	3040	3.00	3.006	2280	36.5	1.788
200 C	12030	5.00	3.40	3040	1.00	3.442	2280	22.6	1.996
300 A	4690	35.0	2.12	3895	0.90	3.646	1679	26.3	1.805
300 B	4690	18.0	2.39	3895	11.0	2.526	1679	15.1	2.046
300 C	4690	10.0	2.64	3895	4.00	2.947	1679	95.8	1.244
400 A	4210	9.00	2.68	3743	7.80	2.681	2836	102.3	1.443
400 B	4210	61.0	1.84	3743	6.70	2.753	2836	45.5	1.805
400 C	4210	13.0	2.49	3743	5.30	2.847	2836	47.4	1.777
500 A	2870	47.0	1.78	4137	47.8	1.937	2786	96.4	1.461
500 B	2870	52.0	1.74	4137	32.9	2.100	2786	173.9	1.205
500 C	2870	18.0	2.19	4137	19.3	2.331	2786	143.4	1.289

Log removal = Log_{10} (Inflow content) - Log_{10} (Filtrate content)

At 15 ^oC there was very little difference exhibited between the three filters for the removal of fecal coliforms although, filter C was again the most effective. For the removal of the total coliform organisms, however, at this temperature (15 ^oC) filter C was more obviously the most effective of the three filters (Table 3). With the removal of both groups of organisms there was again demonstrated a decrease in removal efficiency with increasing rate of treatment, although this was more pronounced at 15 ^oC than it had been at 25 ^oC. Again, at both temperatures (15 ^oC and 25^oC) and for both fecal coliform and total coliform removals the number of 100 % removals declined with increasing rate of flow; this being particularly more pronounced at 15 ^oC.

At the lowest temperature of 5 ^oC there was very little difference evident between the three filters for either the removal of fecal coliforms or for the total coliforms (Tables 3, 4), but for both sets of organisms there was a pronounced reduction in the efficiency of removal as the flow rate increased from 100 mm/h towards 500 mm/h. For the removal of fecal coliforms there were no 100 % removals for the treatment rates higher than 200 mm/h and none at all at any rate of flow for the total coliforms. The log removals of fecal coliforms dropped to as low as 1.019 (filter B) at the treatment rate of 500 mm/h and for total coliform removal at 500 mm/h the lowest log removals were 1.21 (filter B) and 1.29 (filter C).

The effect of temperature was initially not as expected in that the overall removal of both fecal and total coliforms was nearly invariably better at 15 ^oC (Tables 3, 4) than at 25 ^oC. In addition, at the lowest flow rate of 100 mm/h there was very little difference discernible, overall, between the removal efficiencies, for both sets of organisms, at either 25 ^oC or 5 ^oC. However, with increasing rates of flow above 100 mm/h the removal efficiencies declined sharply during the 5^oC investigation and in a far more pronounced manner than was evident at the other two temperatures.

3. 3. Ammonia Removal

A limited number of ammonia determinations were carried out during the investigation (Table 5) and it would be unjustified to draw too rigid conclusions from the information produced.

However, removal of ammonia did occur whether as the result of nitrification or of some other mechanisms. The rate of removal was also fairly obviously, related to temperature, with the overall removal at 25 ^oC being at about 1.4 mg/l, that at 15 ^oC at about 0.56 mg/l and that at 5 ^oC only about 0.23 mg/l. At 25 ^oC it is possible to suggest from the results that the removal decreased with increasing rate of treatment but this is less evident at 15 ^oC and no such indication existed at 5 ^oC. Nor is it possible to draw any conclusions as to the effect of the sand size on ammonia removal during any of three temperature investigations carried out.

At all temperatures there was some limited indication that the removal of ammonia was reflected in the increase in the nitrate concentration in passing through the filters.

Table 5. Ammonia and Nitrate Measurements

Application Flow Rate (mm/h)	Inflow (mg N/l)		Filtrate A (mg N/l)		Filtrate B (mg N/l)		Filtrate C (mg N/l)	
	Ammonia	Nitrate	Ammonia	Nitrate	Ammonia	Nitrate	Ammonia	Nitrate
25 ^oC Period								
100	2.40	3.10	0.03	2.40	0.04	3.20	0.10	3.30
200	2.75	2.05	0.55	2.95	0.37	3.30	0.66	2.90
300	2.00	7.25	1.10	7.25	1.00	7.65	0.56	8.25
400	1.80	5.50	1.00	5.30	0.90	5.00	1.10	5.50
500	1.00	7.00	0.91	6.50	0.10	7.50	0.48	7.00
15 ^oC Period								
100	0.47	3.70	0.02	3.80	0.12	3.50	0.32	3.40
200	1.20	3.30	1.10	3.50	0.09	4.20	0.33	3.70
300	0.80	3.10	0.20	3.20	0.28	3.30	0.53	3.20
400	1.63	2.85	0.14	3.25	0.21	3.30	0.37	3.25
500	0.18	2.47	0.09	2.73	0.07	2.77	0.26	2.87
5 ^oC Period								
100	0.07	2.40	0.02	3.05	0.03	3.20	0.03	2.95
200	0.07	1.90	0.03	2.60	0.01	2.60	0.00	2.60
300	0.28	3.75	0.04	4.35	0.02	4.40	0.14	4.25
400	0.29	4.50	0.32	4.60	0.04	4.40	0.07	4.90
500	1.00	7.50	0.18	6.25	0.51	7.00	0.23	7.75

This phenomenon should not, however, be over-emphasized as the increase in nitrate concentration was always, on average, very limited and, except for the results at 5^{o}C, appreciably less than the removal of ammonia. The initial conclusion drawn from these results had been that either all the ammonia had not been converted into nitrate or, unexpectedly, some definite denitrification had occurred. During the 5 ^{o}C period all removals of ammonia were so small that it can be assumed that the biological mechanisms responsible for this removal were not operable at this low temperature.

It is of some interest to consider further the mechanisms responsible for the removal of the ammonia. Had this been due merely to the biological process of nitrification then an appreciable demand must have been made in the dissolved oxygen in the water present in the filters in that each mg/l of ammoniacal nitrogen converted to Nitrate nitrogen would have required 5.1 mg/l of dissolved oxygen.

Table 6. Dissolved Oxygen (D. O.)

Temperature-Application Flow Rate (^{o}C - mm/h)	Inflow A (mg/l)	Inflow B (mg/l)	Inflow C (mg/l)	Filtrate A (mg/l)	Filtrate B (mg/l)	Filtrate C (mg/l)
15 - 400	5.45	5.40	5.50	4.45	4.30	4.45
15 - 500	7.50	7.40	7.40	6.60	6.80	6.25
5 - 100	7.15	7.10	7.05	5.55	4.60	4.45
5 - 200	6.30	5.95	6.20	4.60	4.10	4.80
5 - 300	6.05	6.15	6.60	4.35	4.80	4.90
5 - 400	6.80	6.50	6.50	4.90	4.70	4.80
5 - 500	8.15	8.05	7.85	5.65	6.00	6.30

A limited number of dissolved oxygen readings were carried out (Table 6), during the course of the whole investigation, of both inlet and outlet dissolved oxygen and these were all made during the 15 ^{o}C and 5 ^{o}C periods. Previously, during the 25 ^{o}C investigation, several tests had indicated that the D.O. content of the water immediately above the sand surface contained about 6 mg/l D.O. The results available however do indicate a fairly consistent removal of about 1.6 mg/l D.O. in the passage through the sand filter.

Similarly relatively a few Total Organic Carbon (TOC) tests were carried out (Table 7) but on average these demonstrated a decrease in TOC content through the filtration process of about 0.7 mg/l which, converted into oxygen demand, gives a figure of 1.9 mg/l. This nearly exactly corresponds to the reduction in the D. O. content.

Table 7. Total Organic Carbon Measurements

Temperature (^{o}C)	Flow Rate (mm/h)	Influent (mg/l)	Filtrate A (mg/l)	Filtrate B (mg/l)	Filtrate C (mg/l)
25	400	3.80	3.90	4.55	3.85
25	500	7.20	4.70	6.70	7.00
15	100	5.50	5.30	5.10	4.90
15	200	3.10	2.45	2.90	2.60
15	300	2.85	2.30	2.50	2.40
15	400	2.60	2.40	2.60	2.40
15	500	7.40	5.70	5.60	5.50
5	100	3.40	2.10	2.05	2.15
5	200	2.51	2.36	2.30	2.34
5	300	6.70	2.72	2.60	2.54
5	400	2.20	2.54	2.04	2.01
5	500	2.83	2.51	2.70	2.68

So the question remains as to what happened to the removed ammonia. The TOC results suggest that all the D.O. removed during the carbonaceous oxidation of organic material and that no demand could have been made on the dissolved oxygen in the water to support a process of nitrification. Thus, there seems to be no case at present to support the possibility of nitrification in these slow sand filters at any of the three temperatures investigated and hence the removal of ammonia must be considered to be the result of anabolic uptake.

3. 4. Run Lengths

Overall it can be suggested that the run lengths for the finest filter (A) are appreciably less than for the other two filters. On average the run lengths at 15 ^{o}C were greater than those at either 25 ^{o}C or 5 ^{o}C for all three filters although this might have had more to do with the quality of the inflow than the effect of temperature. At 25 °C the average lengths of run were 6 days, 25 days and 35 days for filters A, B, and C respectively. At 15 °C the corresponding figures were 10 days, 38 days and 50 days and at 5 °C 9 days, 25 days and 23 days.

4. CONCLUSIONS

Three separate slow sand filters with sand effective sizes of 170, 360 and 450 mm, respectively, were operated at flow rates ranging from 100 to 500 mm/h at three temperatures (25 °C, 15 °C and 5 °C). The results of this research are presented in the following:

1. An acceptable removal of suspended solids was achieved at all flow rates and at all temperatures for all three filters. The removals ranged from 1.77 log (filter C, 25 °C, 100 mm/h) to 0.52 log (filter B, 5 °C, 500 mm/h). The maximum average content of suspended solids in any filtrate was 0.76 mg/l for filter B at 25°C and 500 mm/h.

2. The removal of suspended solids declined with increasing rates of treatment at all three temperatures but was particularly evident at 25 °C.

3. An improved removal of suspended solids was evident from the finest to the coarsest grain filters at 25 °C but less so at 15 °C and not at all at 5 °C.

4. Similar removals of suspended solids were recorded for both the 25°C and 15°C investigations but these declined at 5 °C.

5. The turbidity levels in the filtrates from all the filters were always less than 0.5 NTU although there was a general decline in turbidity removal with decreasing temperature.

6. The average removal of fecal coliform organisms varied from total removal (filters A, B, and C, 15 °C, 100 mm/h) to 1.02 log (filter B, 5 °C, 500 mm/h) and for total coliform organisms from total removal (filter A, 15 °C, 100 mm/h) to 1.21 log (filter B, 5 °C, 500 mm/h).

7. With the exception of the removal of fecal coliforms during the 25 °C investigation there was some definite correlation between the decreasing rate of removal of coliform organism and increasing flow rate.

8. Some definite correlation was evident between improving removal of coliform organisms and increasing sand size at 25 °C but not at the other two temperatures.

9. On the whole the removal of coliform organisms at 15 °C was superior to that at 25 °C. There was also little difference at the lowest rate of treatment (100 mm/h) between the removal of coliform organisms at 25 °C and 5 °C although at higher rates of treatment at 5 °C the rates of removal declined sharply.

10. Ammonia removal was evident at both 25 °C but not at 5 °C although there was little evidence of nitrification.

11. Run lengths for the finest filter (A) were appreciably shorter than for the other two filters.

5. REFERENCES

APHA, AWWA, WPCF, 1989. “Standard Methods For The Examination of Water and Wastewater”, 17 th Edition, Washington DC, USA.

Cox, C. R., 1969.“Operation and Control of Water Treatment Processes”, World Health Organization, Geneva.

Ellis, K.V. and Aydın, M.E. 1993. “A Study of Three Slow Sand Filters at Various Flow Rates with Constant Temperature”, J. Water SRT-Aqua, 42 (2), 88-96.

Ellis, K.V. and Aydın, M. E. 1995. “Penetration of Solids and Biological Activity Into Slow Sand Filters”, Water Research, 29 (5), 1333-1341.

Huisman, L. and Wood, W.E. 1974. “Slow Sand Filtration, World Health Organization, Geneva.

Joshi, N. S., Kelkar, P. S., Dhage, S. S. 1982. Paramasivam, R. and Gadkari, S.K., “Water Quality Changes During Slow Sand Filtration”, Indian J. Environ. Health, 24, 261-276.

Kerkhoven, P. 1979. “Research and Development on Slow Sand Filtration”, World Water, 2, 19-25.

Rachwal, A. J., Bauer, M. J. and West, J. T. 1988. “Advanced Techniques for Upgrading Large-scale Slow Sand Filters”, Slow Sand Filtration: Recent Developments in Water Treatment Technology, Ellis Horwood, New York.

Ridley, J. E. 1967. "Experience in the Use of Slow Sand Filtration, Double Sand Filtration and Microstraining", Proc. Soc. Water Treat. Exam., 16, 170-184.

Thanh, N. C., Wangcharoenwong, W. and Muttamara, S. 1983. "Experience With Slow Sand Filters in Thailand", Chulalongkorn University, Bangkok, Thailand.

Toms, I. P. and Bayley, R. G. 1988. "Slow Sand Filtration: An Approach to Practical Issues", Slow Sand Filtration: Recent Developments in Water Treatment Technology, Ellis Horwood, New York.

Van Dijk, D. C. and Oomen, J. H. 1978. "Slow Sand Filtration For Community Water Supply In Developing Countries: A Design And Construction Manual", WHO, The Netherlands.

Williams, P. G. 1987. "A Study of Bacteria Reduction by Slow Sand Filtration", IWPC Biennial Conference, Port Elizabeth, South Africa, 12-14 May.

Windle-Taylor, E. "The Removal of Viruses by Slow Sand Filtration", Results Bact. Chem. Biol. Exam. Land Waters, 44, 52, 1969-70.

Windle-Taylor, E. 1974. "Bacteriological, Chemical and Biological Examination of London's Water for the Years 1971-73", Metropolitan Water Board, London.