Effect of Fine Sand Size in a Decentralized Household Drinking Water Purification System

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Abstract

Slow sand filtration has been recognized as one of the effective methods of drinking water production in the rural areas of developing countries. In this study, a series of laboratory scale experiments was carried out to study the effects of fine sand size on water filter performance. Two kinds of fine sand, sand A (diameter: 0.5 to 1.18mm) and sand B (diameter: < 1.18mm), were employed during the experiments. The basic experimental unit was an acrylic rectangular tank, 60cm in length, 20cm in width and 70 cm in height. Five compartments were arranged in a way to maximize water purification. Significant improvement was made by using sand B (diameter: < 1.18mm) compared to using sand A (diameter: 0.5 to 1.18mm). It was found that a water filter using sand B was capable of removing more than 85 % suspended solids and 81% turbidity, which were remarkably higher than those by using sand A. Good removal efficiencies for color, iron, manganese, chemical oxygen demand (COD), bacteria and fecal coliform were achieved by using sand B in the unit. The removal for them was 82%, 91%, 93%, 85%, 93% and 100% respectively. Further investigation on the removal efficiency at different stages of unit processes with sand B demonstrated that most of turbidity, color, iron, manganese and fecal coliform were effectively removed after sand bag screening and slow sand filtration. Average removal efficiency was 72%, 64%, 79%, 78% and 93%, respectively. Activated carbon fibre (ACF) played an important role for removing the remaining portion of the contaminants. The resulting removal efficiencies after ACF adsorption for turbidity, color, iron and manganese were 12%, 27.3%, 13% and17% respectively.

Keywords: Slow sand filtration, drinking water, water purification, activated carbon fiber (ACF)

1. Introduction

Slow sand filtration (SSF) has been recognized as one of the effective methods of water purification process in rural areas of developing countries. The world Health Organization (WHO) defines slow sand filtration as the most effective single process in accomplishing the physical, chemical, and bacteriological quality of normal surface water [1]. The unseen processes occurring in a sand bed constitute their effectiveness in purifying water. When water passes through sand, the particles collide with individual grains of sand. Once a particle comes in contact with a grain, it stays attached. The process can be said to be comprised of three stages, collision, attachment, and biodegradation. Its operation and maintenance is cheaper and simpler in comparison to other treatment systems [2]. Sand grains are the essential component of the slow sand filter. Their size and shape are critical in the formation of the biofilm (or schmutzdecke) hence in the effectiveness of the filter as well. Smaller sand grains, with lower porosity give better treatment efficiency. But at the lower porosity water will not flow through it at a reasonable rate causing quick clogging of sand [3, 4]. A suitable fine sand size will provide such a porosity which is small enough to trap particles in water and large enough to let the water flow through and allow some room for biological growth as well[5].

Activated carbon fiber (ACF) has been widely applied to water purification systems in recent years [6]. ACF effectively adsorbs and removes a broad spectrum of harmful substances [7]. ACF can be obtained from appropriate fibrous precursors such as cellulose, resin, pitch or polyacrylonitrile (PAN) fibers, following adequate carbonization and activation [7, 8].

ACF has become popular in water purification processes because of its higher adsorption rate compared to other activated carbon such as granular activated carbon (GAC) or powdered activated carbon (PAC) [8]. The adsorption kinetics and capacities for ACF are 10 to 100 times higher than these traditional adsorbents. It is thought that ACF's faster adsorption rate compared to GAC is due to its higher surface area. It arises from ACF's uniform microporous structure and graphite-like molecular characteristics [9]. To date, most research work is applying slow sand filtration on a much larger scale in centralised water purification systems for urban center [2, 4, 10]. No trials, however, have been attempted to develop an integrated system using slow sand filtration combined with ACF in producing household drinking water. This paper presents the results of the effect of fine sand size in decentralised household water purification systems. A series of laboratory scale experiments was carried out to study the effect of fine sand size on water filter performance. Two kinds of fine sand, sand A (diameter: 0.5 to 1.18mm) and sand B (diameter: < 1.18mm) were adapted in the experiments. Major water quality parameters (physical, inorganic, bacteria and biological parameters) were regularly measured to evaluate the performance of the water filter.

2. Material and method

2.1 Construction of water purification system

Figure 1 shows a schematic diagram of decentralised household water filter. The filter housing was constructed using 10mm acrylic plate (20 x 60 x 70 cm, width x length x height respectively). The unit was designed with five separate compartments to facilitate increased water flow in the system. The function of each compartment is as follows: **A**. Aerated zone with small gravel layer for regulating raw water flow rate, facilitating microorganism growth and reducing odor. **B**. Transition to fine sand filtration. A sand bag packed with fine sand was installed between compartments A and B to act as an initial screen and filter. The sand bag can be easily removed and cleaned if water flow is impeded due to suspended solids. **C**. Down flow slow sand filtration zone. **D**. Up flow slow sand filtration zone. **E**. ACF and effluent zone. In the filtration process, first of all a screening phenomenon occurs on the fine sand bag and then on gravel layer. After that it enters the layer of sand in the filtration zone where both biological activity and filtration occur. Finally the water passes to the ACF and adsorbs the contaminants. For this experiment, the raw water was collected from the surface water ponds adjacent to the Environmental Engineering laboratories, Asian Institute of Technology, Thailand. The influent raw water quality, which varies due to rain, was monitored in the unit with ACF and without ACF. The characteristics of raw water used in the experiment are summarized in Table 1.

2.2 Preparation of fine sand and activated carbon fiber

Physical properties of the fine sand used for slow sand filtration are summarized in Table 2. Due to the high proportion of coarse grain sand, clay and silts, the uniformity coeficient (d_{60}/d_{10}) was found to be 2.4, which exceeds the recommended value of UC ≤ 2. Use of sand having UC value above the recommeneded would result in reduced filtration efficiency. In order to narrow down the sand grain size distribution, it was sieved to prepare sand of size d_{10}= 0.35mm, UC = 2.0 and diameter 0.50 to 1.18 mm. Fig. 2 shows the uniformity coefficient (UC) of the fine sand. Sand was washed several times with the cleanest available water to remove some finer grains of sand.

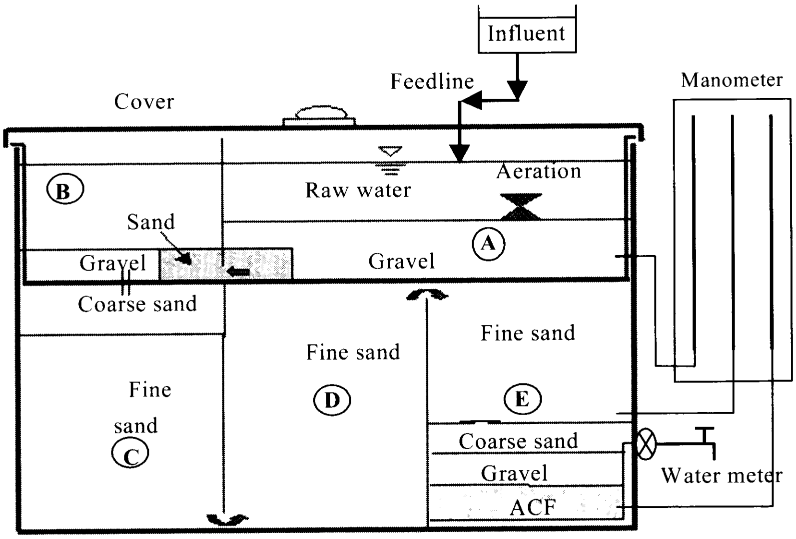

Fig. 1 Schematic diagram of the household water filter

Table 1 Characteristic of raw water

Parameter	Unit	Value
Turbidity	NTU	4.5-18.0
Color	ADMI	4.0-14.0
TSS	mg/L	11.8-23.0
Iron	mg/L	0.10-0.30
Manganese	mg/L	0.20-0.30
Total hardness	mg/L	41.3-74.6
Chlorophyll- A	µg/L	3.2-23.6
COD	mg/L	27.1-32.1
Fecal coliform	CFU/100 mL	4.0-13.0

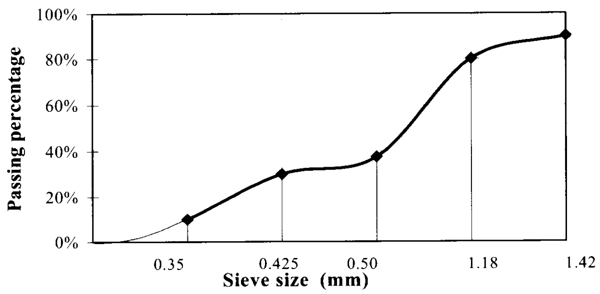

Fig.2 Sieving curve of filter medium

Table. 2 Physical properties of sand medium

Parameter	Value
Coarse sand %	25.7
<2.00mm	71.0
Fine sand % 1.00mm	3.3
Clay and silts	0.49
Porosity	

ACF has widely been applied for drinking water system in recent years. It can effectively adsorb and remove various substances in water due to its uniform microporous structures and higher adsorption rate [9, 12]. In this experiment, ACF was used to remove the remaining portion of contaminants. ACF cartridge was manufactured from Kuractive 16 phenol – resin (Kuraray chemical Co. Japan) [13]. The average diameter of fibre was 14 μm while the fibre the length was 5 mm. The length and diameter of the ACF cartridge were 10 cm and 5 cm, respectively. The filtered effluents were collected inside of the ACF cartridge. Table 3 shows the physical properties of the ACF. The specific surface area of the ACF (1500 m^2/g) was almost 10 to 100 times greater compared to that of GAC (10-150 m^2/g). From the average pore radius and micro - pore volume, it was apparent that micro–pores dominate on the surface of the ACF. Micro–pore portion in this the ACF was found to be 94% (1500 m^2/g out of 1600 m^2/g). Before starting the experiments, the ACF was immersed in distilled water for 24 hours to expel contaminants.

2.3 Experimental operation

The filter was operated manually. A premeasured volume of diluted raw water was poured slowly into the influent tank and the effluent tap was kept open so that water flows freely through each compartment under the influence of gravity. During each subsequent operational phase, flow and pressure head were monitored regularly by using a flow meter and manometer. Average headloss in the unit without ACF was found to be 27.5 cm while it was 34.1 cm with ACF. The filtration rate in the water filter purification system was maintained at 1L/min throughout the operational period. Influent and effluent water quality was regularly analysed following APHA- AWWA – WPCF guidelines using Standard Methods for Examination of Water and Wastewater [14].

Table. 3 Physical properties of ACF

Properties	Unit	Values
Surface area	m^2/g	1,600
Average pore radius	Å	7.7
Micro – pore area	m^2/g	1500
Total - pore volume	cc/g	0.63
Micro - pore volume	cc/g	0.52

3. Results and discussion

3.1 Experiment with mean diameter of 0.5 to 1.18mm

Experimental results with sand A are presented in Table 4. The water filter showed good performance for color, iron, manganese, COD, bacteria and fecal coliform removal. Average removal efficiency of the filter for color was 82% which was higher than conventional slow sand filter (30%) [15].This might be resulted from higher adsorption capacity of ACF. Average removal efficiency for iron and manganese was 89% and 95%, respectively. These results can be caused by ACF catalysis or chemical oxidisation in the autotrophic zone of the water filter [15]. Average COD removal from the unit was 92%. The was due to biodegradation in the sand media and adsorption in ACF. Bacterial and fecal coliform removal from the water was excellent. The unit was efficient for bacteria and fecal coliform removal. Both of them were removed completely from the influent water. Average turbidity and TSS removal with sand A were found to be 72% and 75%, which were lower than experimental data, 80% to 85% [16]. One possible reason is that bigger sized sand mixed into the fine sand, increased the porosity. It decreased the colliding times between particles in water and sand grains. Eventually it influenced the straining activity in the filter to reduce the efficiency.

Table. 4 Experimental results of sand A

Parameter	Unit	Raw water		Treated water		Removal Efficiency (%)	
		Range	Average	Range	Average	Range	Average
Turbidity	NTU	4.5-18.0	9.1	1.0-5.0	2.6	71-83	72
Color	Hagen	13.0- 40.0	22.1	<5.0	<5.0	-	-
	ADMI	4.0-14.0	10.0	<3.0	1.8	82	82
TSS	mg/L	11.8-23.0	17.5	0.01-0.12	4.4	70-80	75
Iron	mg/L	0.10-0.30	0.20	<0.04	0.02	70-94	89
Manganese	mg/L	0.25-0.30	0.23	34.1-50.2	0.01	87-100	95
Total hardness	mg/L	41.3-74.6	54.4	0.0	43.1	0	0
Chlorophyll- A	µg/L	3.2-23.6	6.8	0.8-3.2	0.0	100	100
COD	mg/L	27.1-32.1	21.3	0.0	1.6	90-97	92
Fecal coliform	CFU/100 mL	4.0-13.0	8.5		0.0	100	100

3.2 Experiment with mean diameter < 1.18mm

Experimental results with sand B is summarized in Table 5. Effluent quality with sand B was found to be better than that with sand A. Average removal efficiency for turbidity improved from 72% to 81%. Compared with the result of sand A, a higher average removal efficiency of 86%, was achieved for TSS in sand B. These suggest that particles such as silt and clay, finer than sand, can attach other particles by electrical forces, chemical bonds and mass attraction [17]. On the other hand, silt and clay fills the voids in between the large grains, reducing the porosity of sand in the filter. The water filter showed good removal efficiency for color, manganese, COD, bacteria and fecal coliform as well. Average removal efficiencies were found to be 82%, 91%, 85%, 93% and 100% respectively. As a result of using a wide range of fine sand size in experiments with sand B, a thin slimy matting (named schmutzdecke or biofilm) developed on the surfaces of both fine sand grains in the sand bag and the small gravel layer. Sand B contains 5.2 % silt and clay which helps to create a lower porosity. This results in improvement in the effective colliding between particles and sand grain. Once particles come in contact with a grain, they develope into a dense population referred to as a schmutzdecke or biofilm. These particles are then consumed as a food source in biodegradation processes [3]. ACF also plays an important role for removing contaminant by adsorption phenomenon.

Table. 5 Experimental results with sand B

Parameter	Unit	Raw water		Treated water		Removal efficiency (%)	
		Range	Average	Range	Average	Range	Average
Turbidity	NTU	4.0-16.0	6.6	0.5-3.0	1.3	60-91	81
Color	ADMI	5.0-12.0	9.2	0.0-3.0	1.6	67-100	82
TSS	mg/L	5.0-19.5	10.8	0.5-3.0	1.4	70-96	86
Iron	mg/L	0.1-0.7	0.3	0.002-0.05	0.021	80-99	91
Manganese	mg/L	0.03-0.15	0.10	0.00-0.01	0.006	81-100	93
Total hardness	mg/L	63.7-71.8	67.4	67.8-75.5	71.7	0	0
Chlorophyll-	µg/L	3.3-17.6	10.5	0-1.5	0.74	92-100	93
A	mg/L	28.5-72.2	51.1	5.3-10.9	6.9	79-90	85
COD	CFU/1	10	10	0.0	0.0	100	100
Fecal coliform	00 mL						

Table. 6 Average removal efficiencies for different water quality parameters

Parameter	Sand A (%)	Sand B (%)	Increments (%)
Turbidity	72	81	9
Color	82	82	-
TSS	75	86	11
Iron	89	91	2
Manganese	95	93	-
Total hardness	0	0	-
Chlorophyll- A	100	93	-
COD	92	85	-
Fecal coliform	100	100	-

Table 6 summarizes the average removal efficiencies for different water quality parameters analyzed in the experiment. In both the cases, higher removal of color, manganese, COD, bacteria and fecal coliform were found from the unit. Experiments with sand B showed improvement in the performance of removal efficiency by 11%, 9%, and 2% for TSS, Turbidity, and iron respectively.

3.3 Evaluation of various unit processes

Water filter showed good performance with sand B. Further investigation was carried out using sand B to find the removal efficiencies at different stages of unit processes in the filter. To investigate the performance of the water filter, raw water, outlet from fine sand bag, slow sand filtration, and ACF, were measured at regular time intervals.

Figure 3 shows turbidity removal at different stages of unit processes. Influent raw water turbidity varied from 6.4 NTU to 3.0 NTU. The removal efficiency of the fine sand bag was 33.3% to 45.3% with corresponding turbidity of 2.0 NTU. The turbidity dropped from 2.0 NTU to 1 NTU when it passed through the sand filtration. Final turbidity after ACF was found as 0.51 NTU. Turbidity removal from the sand bag and SSF alone was 72.4 % indicating the effectiveness of screening and SSF.

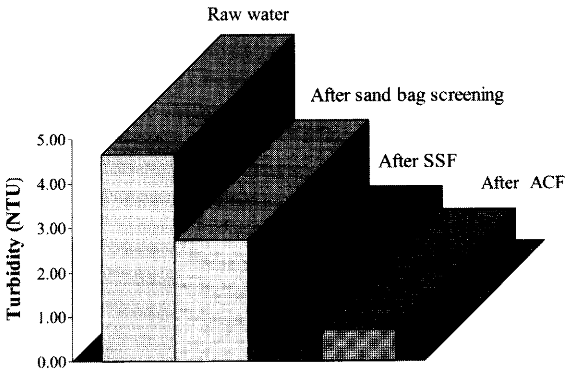

Fig. 3 Decrease of turbidity at various steps of unit processes

Color removal at different stages of unit processes is shown in Fig. 4. About 40% of color was removed by the fine sand screen alone. This result suggests that the biofilm that developed on both the sand bag and the small gravel, broke down some impurities by bio-chemical processes [18]. 27.3% of color was removed by ACF while SSF removed 24%. Each compartment was effective in removing color from the influent water.

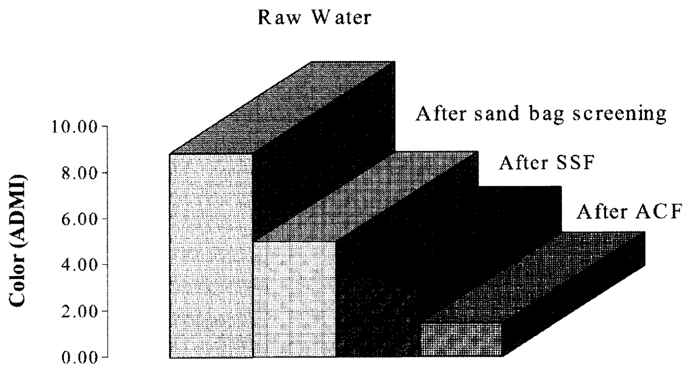

Fig. 4 Decrease of color at various steps of unit processes

The efficiency of the filter on the removal of iron and manganese is as shown in Figure 5 and Figure 6. After sand bag screening, the average removal efficiency was 24%

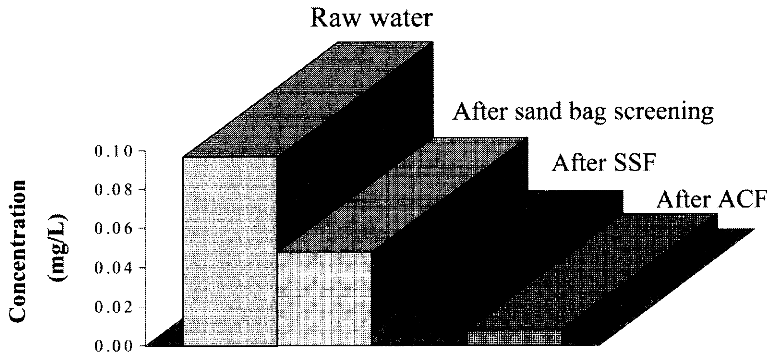

Fig. 5 Decrease of iron at various steps of unit processes

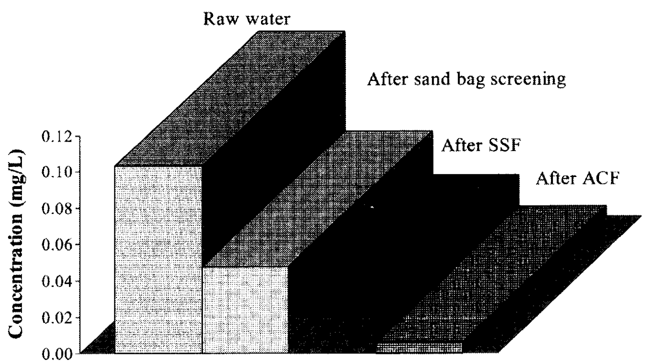

Fig. 6 Decrease of manganese at various steps of unit processes

The efficiency of the filter on the removal of iron and manganese is as shown in Figure 5 and Figure 6. After sand bag screening the average removal efficiency was 51% and 54 %, respectively, for iron and manganese. After slow sand filtration, 28% of iron and 24% manganese were effectively removed. The average removal of iron and manganese were found to be 13% and 17%, respectively, after ACF adsorption. These results indicated that most of the iron and manganese were remarkably reduced after sand bag screening and slow sand filtration. Average removal efficiency of iron and manganese after sand bag screening and slow sand filtration were 79% and 78%, respectively. Additionally, ACF showed higher adsorption for the remaining manganese (17%) reduction compared to the remaining iron reduction (13%) in the water.

Fecal coliform was examined to investigate bacteria and viruses removal from the system. The number of fecal coliform was reduced from 10CFU/100mL to 6CFU/100mL after passing through the sand bag screening. After passing through slow sand filtration it was reduced to zero. These results were caused by biofilm, which consumed organic and inorganic particles in water, the food source of fecal coliform, via biodegradation processes which occurred at both the fine sand bag and small gravel [19]. Due to the lack of food source, most fecal coliform died after sand bag screening and slow sand filtration processes. Sand bag screening and slow sand filtration played an important role for fecal coliform removal.

4. Conclusion

Performance of the sand filter with sand B (<1.18 mm size) was better than with sand A (0.5 to 1.18mm in size) for removing most of the water contaminants studied. It was found that (1) removal efficiencies of turbidity and TSS increased to 81% and 86%, compared to 72% and 75% respectively with sand A. (2) High levels, of color, manganese, COD, bacteria and fecal coliform removals were achieved with sand B. Average removal efficiencies for them were found to be 82%, 91%, 85%, 93% and 100%, respectively (3) Further investigation about removal efficiencies at different stages of unit processes with sand B shows that most of turbidity, color, iron and manganese were significantly reduced after sand bag screening, due to biodegradation processes on the biofilm. Average removal efficiency was 40%, 40%, 51%, 53% and 33%, respectively, for them. After slow sand filtration, 32% of turbidity, 24% of color, 28% of iron, 24% of manganese and 60% of fecal coliform were effectively removed. ACF played an important role for removing the remaining portion of contaminants. Average removal by ACF for turbidity, color, iron and manganese were found to be 12%, 27.3%, 13% and 17%, respectively. ACF had no effect on fecal coliform removal since all of the coliform was removed after the sand bag screening and slow sand filtration.

5. Acknowledgement

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6. Reference

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