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Original Article

Hydraulics and Dynamics of Backwash in Filtration with Activated Carbon to Reduce Iron and Manganese in Groundwater

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Abstract— Well water used by the community often does not meet quality standards because it contains high levels of iron (Fe) and manganese (Mn). This study was intended to reduce Fe and Mn levels in well water by using filtration technique with activated charcoal media. The effect of hydraulics and backwash dynamics on the efficiency of filtration process was also investigated. The filtration apparatus was made of PVC pipe with the diameter of 4 inches and 120 cm height. The determination of optimum hydraulic conditions of filtration was carried out by varying the size of the activated carbon filter media (8-10, 12-14, and 16-18 mesh) and flow rate (1, 2, and 3 L/min) at the service time of 10 hours. The results showed that the size of filter media has significant effect on removal efficiency of Fe and Mn, with the most effective size was 16-18 mesh with the removal efficiency of 83.33% (Fe) and 93.33% (Mn). The highest head loss value in the filtration column was 0.15 cm, which occurred at the flow rate 3 L/min. Backwash should be performed after filtering process of 35 hours, 44 hours and 55 hours at the flow rate 1 L/min, 2 L/min, and 3 L/min repectively. The single filter design in this study reduced Fe and Mn concentration to meet clean water quality standards.

Keywords—*Adsorption; Flow rate; Head loss; Reynolds number; Well water quality*

1. INTRODUCTION

The availability of clean water is one of the most important conditions in improving human health and reducing the impact of poverty [1]. Currently, the utilization of groundwater for domestic and household needs remains very high, although the quality of groundwater does not always meet the quality standards. This situation for instance has been happening in Baran Hamlet, Pundong District, Bantul Regency, Special Region of Yogyakarta. The previous research showed that the groundwater in Baran Hamlet is contaminated with iron (Fe) and manganese (Mn), with the concentrations of 0.05 mg/l and Mn 2.10 mg/L, respectively [2]. The groundwater that contaminated with Fe and Mn could causes various negative impacts on human health. Excessive concentrations of Fe could cause eye and skin irritations as well as damaging kidney function. High levels Mn in water could result in nervous system disorders, skin problems, and brain damage [3].

Monitoring and controlling Fe and Mn levels in groundwater are very important to ensure the safety and suitability of the water for consumption and for other uses. The standard quality of Fe and Mn concentration in water for sanitation purposes according to the Indonesian Minister of Health Regulation number 2, 2023 are 0.1 and 0.2 mg/L, respectively. Reducing Fe and Mn levels to meet quality standards can be achieved by filtration methods. Another alternative to reduce Fe and Mn concentrations in water is through oxidation process such as aeration, administration of chlorine or potassium permanganate, and/or ozone doses, then followed by filtration [4]. However, among those various techniques, filtration procedure is considered more suitable to implement in removing or reducing Fe and Mn levels in rural areas because it is relatively inexpensive and easy to operate.

Filtration is a process process to remove impurity particles in a fluid based on the the difference in interaction between filter and filtrate [5]. Most filtration processes involve adsorption, which is the process of adsorbate absorption on the adsorbent surface, either chemically (chemisorption) or physically (physisorption).

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One of the filter media that is often used in water purification is activated carbon. This material is generally used as the adsorbent to remove organic micropollutants, and however only a little is known for the removal of inorganic pollutants [6]. The application of activated carbon in removing metal ion such as Fe and Mn are generally in the combination with other filter media, such as zeolite [7,8], sand [9,10], and manganese greensand [10]. However, the use of activated carbon as a single filter also shows good effectiveness in removing Fe and Mn as demonstrated by Wahyuni (2019) [11], in which the removal efficiencies recorded were 39.38% and 81.82% for Fe and Mn respectively. Fe and Mn removal efficiencies of 71.9% and 75.4% were achieved by employing biologically modified activated carbon filters [12].

The filtration process has several important stages [13]. When filtration begins, particles carried by water will be trapped in the filter media. Over the time, these particles will fill up the pores of the media, which is resulting in an increase in head loss in the filter media. An increase in head loss can be observed as the water surface above the filter media rises or the filtration discharge decreases. When head loss occurs beyond the permitted point due to blockage of the filter pores, then backwass procedure is required to perform to clean the filter media and to return its shape. According to Zeng et al. (2015) [14], backwashing can remove more than 50% of the total Fe and Mn in the filter column and renew the Fe and Mn removal capacity. Understanding how particle size and flow rate affect filtration efficiency, as well as how backwash effect on head loss and particle release, could significantly improve water treatment processes [14,15]. Therefore, this research emphasizes on the hydraulics aspects (particle size, flow rate, and head loss) as well as backwash dynamics in filtration process to reduce Fe and Mn concentration in groundwater by using activated carbon filter media. The Fe and Mn removal mechanism in this study, in addition to the filtration process, also involves an adsorption process, so this study will also investigate this possibility.

2. EXPERIMENTAL SECTION

2.1. Materials

The groundwater samples were taken from one of the residents' wells in Baran Hamlet area, Pundong District, Bantul Regency, Special Region of Yogyakarta. The initial 6 samples for a pre-trial were taken from residents' houses in RT 2, 3, 5, 7, and 8 of Pundong Hamlet. The sample that used as the basis for design calculations was sample number 5 with the highest manganese content of 2.1 mg/L.

2.2. Instrumentation

The apparatus employed in this study was filtration unit made of PVC pipe with the diameter of 10 cm and the height of 120 cm. The filter unit was equipped with ball valve to regulate the filtration outflow. The activated carbon used was commercial product with the brand name Haycarb. Other tool used in this study was mesh sieving to obain the activated carbon with the size of 8 mesh, 10 mesh, 12 mesh, 14 mesh, 16 mesh, and 18 mesh. The balance was employed to weigh the activated charcoal to be used, an atomic absorption spectrophotometer (AAS) to analyse Fe and Mn concentration, a stopwatch to measure the discharge time, a camera for documentation, and sample bottles to keep the samples.

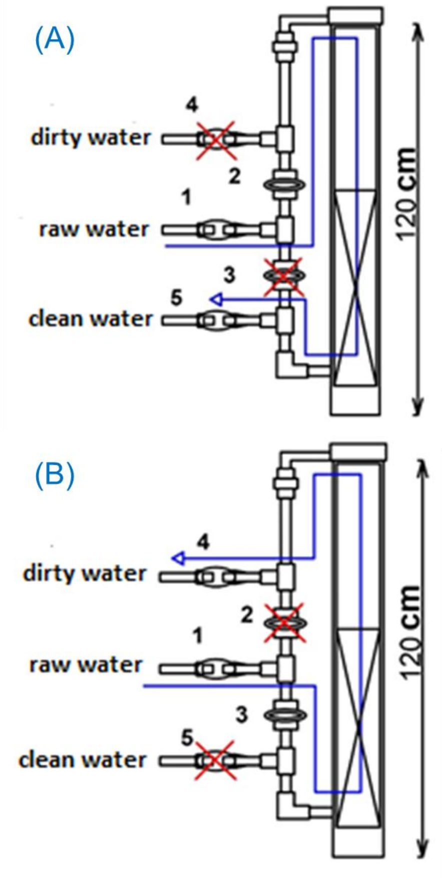

Figure 1. Filtration arrangement (A) normal flow, (B) backwash flow

Figure 1 shows the illustration of filtration unit used in this study, which is including the components of the filtration device and its water flow diagram. Valve number 1 is for inlet, while valve number 4 and 5 are for outlet. The clean water flows through outlet during the filtration process, while dirty water flows out through the outlet after the backwash process. During the filtration process, named running, the water flows downward from the top to the bottom of the filter unit. During backwashing to clean the filtration media, water flow patern was reversed from the bottom of the device to the top.

2.3. Filtration Process

The effects of hydraulic parameters, such as media size and flow rate, on filtration rates were investigated before and after backwash. In addition to the two parameters, the extent of head loss during running was also investigated. The effect of media size was investigated by conducting the trials on different media sizes, in the same media thickness, flow rate, and initial concentration of Fe and Mn, which were 0.60 mg/l for Fe and 1.5 mg/L for Mn.

Prior to the filtration process, the filter media was sieved into 3 different sizes of 10/12, 14/16, and 18/20 mesh. After sieving procedures, the filter media was packed into filter column to 60 cm height. The sample water was then flowed for 10 hours. At the 10th hour, the sample was taken for analyses and then backwash was carried out for 15 mins. At the end of backwash, the water sample was taken again. The analyses to check Fe and Mn concentration was performed by using AAS instrument. In this pre-trial, the activated carbon size which gave the highest flow rate then used in the run with flow rate variation of 1 L/min, 2 L/min, and 3 L/min. The samples were taken every hour during 10-hour filtration process to analyse Fe and Mn concentrations.

2.4. Data Analysis

Filtration removal efficiency was evaluated by using Equation (1).

$$\mathbf{E} = \frac{C_{initial} - C_{end}}{C_{initial}} \times 100\% \qquad (1)$$

Where E is Removal Efficiency (%), and C is Concentration

Head loss calculation was done by using Darcy-Weibach equation [15], which is shown in Equation (2).

$$h_f = \frac{f' L(1-e)V^2}{e^3 g\, d} \qquad (2)$$

Where h_f is Head loss (m), f' is Coefficient of friction, L is Column depth (m), e is Void ratio, V is Filtration velocity (m/s), g is Acceleration rate due to gravity (m/s²), d is Diameter of filter media (mm).

The friction coefficient, Reynolds number, and filtration velocity were calculated using equations (3), (4), and (5).

$$f' = \frac{150(1-e)}{Re} + 1.75 \qquad (3)$$

$$Re = \frac{\Psi \rho V d}{\mu} \qquad (4)$$

$$V = \frac{Q}{A} \qquad (5)$$

Where Re is Reynolds number, ρ is Density of water (kg/m^3), Ψ is Shape factor, μ is Water viscosity (kg/m.s), V is Filtration velocity (m/s), d is filter media diameter (mm), Q is Flow rate (L/min), A is Surface area of filtration column (m^2).

Backwash time was calculated by using the following regression formula:

$$Q = \bar{Q} + \frac{\sum(t-\bar{t})(Q-\bar{Q})}{\sum(t-\bar{t})^2}(t-\bar{t}) \qquad (6)$$

Where $\bar{\mathbf{Q}}$ is Average discharge (m^3), t is Time (Hours), $\bar{t}$ is Average time (Hours).

3. RESULT AND DISCUSSION

3.1. Results of The Filtration Process Before and After Backwash

This research was conducted by using groundwater obtained from wells which are located in Baran Hamlet, Pundong District, Bantul Regency, Special Region of Yogyakarta. Fe and Mn concentrations in water samples before and after backwash, were presented in Table 1. The samples were obtained from one of the wells in RT 5 Padukuhan Baran. The concentrations of Fe and Mn in the samples were very high, which were exceeding the standards stipulated in Minister of Health Regulation No. 2, 2023.

Table 1 also shows that during both before and after backwash, the smaller of the particle size of the filter media results in the greater decrease in metal concentration. The smallest media size of 16-18 mesh gives the highest metals removal efficiency, which were 83.33% for Fe and 93.33% for Mn (before backwash) and 90.00% for Fe and 90.00% for Mn (after backwash). Thesree a due to the smaller the size of the activated carbon, the larger surface area of the activated carbon, so that the adsorption capacity becomes higher. Adsorption is a mechanism that reduce Fe and Mn during filtration process that using activated carbon [16]. In another study, the effectiveness of activated carbon in removing micropollutants was closely related to its particle size. Smaller activated carbon particles increased turbidity in wastewater, where a four-fold size reduction caused a 2-3-fold increase in turbidity [17].

Fe and Mn removal efficiency after backwash was ranged from 70% to 90%. The most efficient activated carbon size was 16-18 mesh with concentration reduction of 90% for both for Fe and Mn. The analysis of Fe and Mn concentrations after backwash confirmed that the size of activated carbon affected the removal efficiency. The efficiency of Fe and Mn removal increased immediately after backwash. This phenomena occured because during the backwash, Fe and Mn which were trapped in the pores of the activated carbon were eroded and swept away by backwash water. Another study showed that the backwashing strategy could reduce head loss by 11-18%, thereby increasing filtration efficiency [18]. Based on the results, it was concluded that the filtration column using activated carbon as the filtering media reduced Fe and Mn concentrations in groundwater, and the concentration met the quality standards stipulated by the Regulation of the Minister of Health of Indonesia Number 2, 2023.

Table 1. Iron (Fe) and Mn concentrations before and after backwash

Element	Activated Carbon Diameter (mesh)	Beginning (Before Treatment) (mg/L)	End (After Treatment) (mg/L)	Decrease (mg/L)	Percentage Decrease	Minister of Health Regulation No. 2, 2023
			Before Backwash			
Fe	8-10	0.60	0.20	0.4	66.66%	
	12-14	0.60	0.10	0.5	83.33%	0.1 mg/L
	16-18	0.60	0.10	0.5	83.33%	
Mn	8-10	1.5	0.15	1.35	90.00%	
	12-14	1.5	0.12	1.37	91.33%	0.2 mg/L
	16-18	1.5	0.10	1.40	93.33%	
			After Backwash			
Fe	8-10	0.20	0.06	0.14	70.00%	
	12-14	0.10	0.02	0.08	80.00%	0.1 mg/L
	16-18	0.10	0.01	0.09	90.00%	
Mn	8-10	0.15	0.05	0.1	70.00%	
	12-14	0.12	0.03	0.09	75.00%	0.2 mg/L
	16-18	0.10	0.01	0.09	90.00%	

3.2. The Effect of Continuous Flow Rate Variation and Head Loss Calculation

The most effective media size (16-18 mesh) was then utilized to investigate the effect of flow rate variations, which were 1 L/min, 2 L/min, and 3 L/min. The filtration operation involved filtering particles contained in the grondwater by filter media. The particles trapped in the filter media will accumulate by time so that they clog the pores of the media (clogging). The clogging will increase the flow resistance, which in return increasing pressure loss in the filter bed, or known as the head loss in the media bed [19]. The increase in head loss could also be observed as the water level above the media increase or the decrease in water outflow.

The quantity of head loss could be calculated using Equation 2. The Reynold number (Re) was calculated using the following data: filter media (activated carbon) diameter (d) = 1.8x10^{-3} m, temperature 28 ºC, water viscosity coefficient (μ) = 0.883 x 10^{-3} kg/m.s; shape factor (Ψ) = 0.98, flow rate 1 L/min, acceleration due to gravity = 9.8 m/s^2, and water specific gravity = 1000 kg/m^3. The head loss for the flow rate 1 L/min then could be calculated as follow:

Calculation of Reynolds Number (Re)

$$\mathrm{Re} = \frac{\Psi \rho V d}{\mu}$$

$$\mathrm{Re} = \frac{0.98 \times 1000\ \mathrm{kg/m^3} \times 4.42 \times 10^{-5}\ \mathrm{m/s} \times 1.8 \times 10^{-3}\,\mathrm{m}}{0.883 \times 10^{-3}\ \mathrm{kg/m.s}}$$

$$\mathrm{Re} = 0.088\ \text{(laminar flow)}$$

Calculation of Friction Coefficient (f')

$$f' = \frac{150(1-e)}{\mathrm{Re}} + 1.75$$

$$f' = \frac{150\,(1-0.49)}{0.088} + 1.75$$

$$f' = 867.49$$

Head loss (hf) calculation

$$hf = \frac{f' L (1-e)\, V_s^{\,2}}{e^3 g d}$$

$$hf = \frac{867.49 \times 1.2\ \mathrm{m} \times (1-0.49)(4.42 \times 10^{-5}\,\mathrm{m/s})^2}{(0.49)^3 \times 9.81\,\mathrm{m/s^2} \times 1.8 \times 10^{-3}\,\mathrm{m}}$$

$$hf = 0.0005\ \mathrm{m} = 0.05\ \mathrm{cm}$$

From the calculation, the head loss was 0.05 cm at the flow rate 1 L/min. The head loss at the 2nd hour and so on until the end of trial (10th hour) could be evaluated by using the same procedure, as well as at the flow rates of 2 L/min and 3 L/min. Head loss value for each flow rate is presented in **Table 2**.

The highest head loss recorded at flow rate 3 L/min or at the highest rate in this study. Therefore, it can be concluded that the higher flow rate result in the higher head loss. This outcome is in accordance with the conclusion proposed from the previous research conducted by Oktiawan and Krisbiantoro (2007) [20]. Even though the filter media was different (active sand), the result was similar in which the larger flow rate was

Table 2. Head loss of the flow rate 1 l/min, 2 l/min, and 3 l/min

Debit (Q) (L/min)	Reynolds number (Re)	Friction force (f')	Head loss (hf) (cm)
1 L/min	0.088	867.49	0.05
2 L/min	0.177	434.62	0.10
3 L/min	0.265	290.33	0.15

directly proportional to the head loss value. Furthermore, the Reynolds number is aslo directly proportional to the flow rate. The Reynolds number in all of three flow rates variations indicated the laminar flow, in which Re < 2300 [21,22]. These results are in accordance with conclusion proposed by Siswanto (2016) that the Reynolds number is directly proportional to the flow velocity [23]. The greater the fluid flow velocity, the higher the Reynolds number, so that the friction coefficient value (f') as well as the head loss are larger. Furthermore, the increase in water velocity that going through filter column causes more compression in filter bed, so then the void space among the filter media particles will reduce.

Fe and Mn dissolved in water are generally in the form of Fe^{2+} or Mn^{2+} ions, which will slowly oxidize into ferric compounds $Fe(OH)_3$, and manganoxide compounds MnO_2. These compounds are insoluble in water to develop clumps (flocs) [24]. In reality, the formation of Fe and Mn flocs generally occurs when water flows into the reservoir; then the oxidation process take place between iron and manganese in water with oxygen in the air. The chemical reactions occured as follow [24]:

$$4Fe^{2+}_{(aq)} + O_{2\,(g)} + 10H_2O_{\,(l)} \rightarrow 4\,Fe(OH)_{3\,(s)} + 8H^{+}_{\,(aq)} \tag{7}$$

$$2Mn^{2+}_{(aq)} + O_{2\,(g)} + 2H_2O_{\,(l)} \rightarrow 2MnO_{2\,(s)} + 4H^{+}_{\,(aq)} \tag{8}$$

The remaining concentrations of Fe and Mn in dissolved form (Fe^{2+} and Mn^{2+}) in water will be adsorbed on the surface of activated carbon due to unbalanced forces at the interface, which then causes an increase in the number of particles in the activated carbon media. The adsorption properties of activated carbon are promoted by the presence of the large number of pore structures and influenced by the chemical composition that caused by the irregularity of the microstructure. The presence of large and wide pores stimulate the capillary symptoms so that the adsorption process occurs. According to Mwanat et al. [16], Fe^{2+} and Mn^{2+} adsorption processes in activated carbon could happen either chemically or physically. The physical interaction between Fe^{2+} and Mn^{2+} with activated carbon is caused by the weak Van Der Waals force between the adsorbate molecules and the adsorbent molecules, resulting in the adsorbate binding to the adsorbent molecules. The bond can be broken by the kinetic force arising from the water at a certain velocity during the backwash phase.

3.3. Backwash Time Estimate with Regression Formula

Rapid filtration process usually has a relatively short service life; or in other words, filter clogging is easier to occur. Cleaning the filter media for rapid filter is performed by flowing water in the opposite direction to the flow direction during filtration. The surface of activated carbon that has already been saturated with Fe and Mn which are physically absorbed during the filtration process would be eroded by the reverse flow of water. As the result, the pores will be cleaned and opened again and the activated carbon can be reused as a filter media again. During backwash process, the materials that clog the filter will also be let loose and will be swept away by the rinsing water, so backwash is also a process of regenerating the filter media capability to filter and to absorb. The filter media regeneration process in this study is aduaquate with reversing flow (upflow) procedure, which is much cheaper than if the regeneration process is carried out chemically as in common practice exchange resin regeneration.

Filtration column that was operated in a long period will produce smaller outflow. The decrease in outflow during the trials with the flow rate of 1 L/min, 2 L/min, and 3 L/min during the 10-hour operation is presented in **Table 3**. The flow measurement was carried out every hour.

The regression formula then be used to predict when the flow will stop or Q will be 0 according to equation 6. The regression equation for Q = 1000 mL/min is Q = 1007.65 – 14.3 t, and it was predicted that the flow rate Q will reach 0 or the water flow will stop flowing after 70 hours operation. With the same procedure, at the variations flow rate of 2 L/min and 3 L/min, the flow rate was predicted to reach zero after the filtration column has been operated for 88 and 109 hours, respectively.

The higher the flow rate, the longer the clogging will

Table 3. Decrease in filtrate discharge with the flow rate of 1 L/min, 2 L/min, and 3 L/min

No	t	Q 1000 mL/min	Q 2000 mL/min	Q 3000 mL/min
1	0	1000	2000	3000
2	1	1000	1990	2930
3	2	980	1950	2850
4	3	950	1950	2800
5	4	950	1935	2790
6	5	940	1900	2775
7	6	935	1850	2750
8	7	900	1850	2750
9	8	890	1830	2735
10	9	875	1800	2730
11	10	870	1790	2720
Regression equation		Q = 1007.65 – 14.3 t	Q = 2009.625 – 22.75 t	Q = 2956.66 - 27.03 t
Slope		14.3	22.75	27.03

occur. The results indicated that the flow rate of 3 L/min will stop in longer time than the flow rates of 1 L/min and 2 L/min, so its operation will be more efficient for longer operation time before backwash.

The calculation using regression formula is to extrapolate the results beyond 10 hours run in order to predict the operating time before the flow stops completely in the filtration column. However, it is better to wash the filter media before the flow is completely stop to maintain the filtration unit optimal operation. The decrease in filtrate flow in the three flow rate variations was assumed linear. It is recommended that if the flow rate has decreased by 50%, backwash should be performed, which are after 35 hours, 44 hours and 55 hours at the flow rate of 1 L/min, 2 L/min, and 3 L/min respectively.

4. CONCLUSION

The single filter bed with activated carbon media was capable to reduce Fe and Mn concentrations in groundwater to meet clean water quality standards. The highest Fe and Mn removal efficiency during 10-hour service time was 83.33% (Fe) and 93.33% (Mn) by using 16-18 mesh filter media. The size of the activated carbon media affects the removal efficiency. The highest head loss value was observed at flow rate of 3 L/min which was 0.15 cm and did not exceed 20% of the height of the empty space above the media bed in the filter column. The estimated operating time (service time) of the filter column before backwashing was 70 hours for flow rate of 1 L/min, 88 hours for flow rate of 2 L/min, and 109 hours for flow rate of 3 L/min. However, backwashing should be carried out when the flow rate has decreased by 50%, which are 35 hours, 44 hours and 55 hours for the flow rate of 1 L/min, 2 L/min, and 3 L/min. This study also helps to provide a simple, inexpensive, and easy-to-operate-single media filtration column design for the treatment of groundwater that containing high Fe and Mn concentrations. Further research is recommended to perform in order to determine how long the activated carbon could be used until it can no longer be regenerated by backwashing, so that the media replacement is required.

SUPPROTING INFORMATION

There is no supporting information in this paper. The data supporting this research's findings are available on request from the corresponding author (ADNL).

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CONFLICT OF INTEREST

There was no conflict of interest in this study.

AUTHOR CONTRIBUTIONS

NI revised the manuscript, IS conducted the experiment, DE revised the calculations and the manuscript, ADNL wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

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