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The effect of high hydraulic loading rate on the removal efficiency of a quadruple media filter for tertiary wastewater treatment

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ABSTRACT

It is well known that filtration removal efficiency falls with an increase in flow rate; however, there is limited supporting experimental data on how removal efficiency changes for filters with multiple layers of media and for wastewater filtration, a practice that is becoming more common. Furthermore, information is not available on the characteristics of particles that are removed at different flow rates. Here, a quadruple media filter was operated at hydraulic loading rates (HLRs) between 5 and 60 mh^{-1} with subsequent measurement of total suspended solids, turbidity and particle size distribution (PSD). Samples were collected from the filter influent, effluent and also from between media layers. Pressure changes across the filter layers were also measured. The solids removal efficiency of the filter varied inversely with the increase in filtration rate. However, the multiple media layers reduced the negative impact of increased HLR in comparison to a single media filter. High filtration rates were shown to transport solids, such that particle retention and headloss development was distributed across the entire depth of the multi-media filter. There was also a progressive decrease in the suspension particle size leaving each of the filter layers. The particle hydrodynamic force simulation was consistent with the changes in measured PSD through the filter layers.

1. Introduction

Granular media filtration is one of the oldest forms of treatment technology used in the production of potable water and is still widely used due to its reliability and low cost (Burton et al., 2003; Han et al., 2009; Kim and Lawler, 2012). However, the filtration of wastewater secondary effluent is a relatively recent practice in situations that demand high water quality. This includes tertiary treatment of wastewater for water reuse in water stressed areas (Bloetscher et al., 2014; Christou et al., 2014; Ho et al., 2011), or to meet the standards required for discharge to sensitive water courses and drinking water protected areas (Defra, 2012).

Granular media filtration removes suspended solids and colloidal particles, which includes particulate biochemical oxygen demand (BOD), chemical oxygen demand (COD), microbes and other suspended chemical contaminants from wastewater secondary effluent (Illueca-Muñoz et al., 2008). Removal of solids is also necessary prior to chemical and UV disinfection that may be used for wastewater reclamation (Lazarova et al., 1999; Williams et al., 2007) by reducing shielding of viruses by solid particles (Kirkpatrick and Asano, 1986). In the UK, tertiary filtration of wastewater secondary effluent is usually necessary in environmentally sensitive areas where tight regulatory discharge requirements are needed. Tertiary treatment is therefore becoming more common to safeguard public health as well as to minimise pollution (Ho et al., 2011; Langenbach et al., 2010; Li et al., 2012).

Filtration of wastewater is significantly more challenging than for potable water due to the higher solid loads, much of which is organic in nature. To illustrate, the average influent turbidity to a drinking water works filtration system is typically around 1 NTU with occasional spikes up to 8 NTU (Zouboulis et al., 2007). However, secondary effluents typically have turbidity between 5 and 20 NTU (TSS 10–40 mg L^{-1}) which causes rapid headloss development in most conventional mono-media filters (Aronino et al., 2009; Lander, 1994). Aronino et al. (2009) observed cake formation on a single media depth filter treating wastewater secondary effluent and while the filter was effective for virus removal, the headloss build up was rapid. The increase in normalised headloss (NHL) per filtered volume was 1.65 $(m^3/m^{-2})^{-1}$ at a filtration rate of 5 mh^{-1}. Rapid headloss development shortens the filter runs and hence

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results in a low product water throughput before backwash is necessary.

One of the reasons for rapid headloss development in conventional mono-media filters is because the backwash cycle leads to media stratification, with small media grains at the top and large grains at the bottom (Baruth, 2005). The stratified arrangement leads to accumulation of the solids in the top layer in the subsequent filter cycle and hence results in underuse of the rest of the filter depth for solid retention. One proprietary mono-media filter (the Tetra filtration system) overcomes this through the use of coarse media of uniform size to discourage size stratification and also to promote deep penetration of solids (Crittenden et al., 2012). Use of coarse media, however, has a disadvantage in that it reduces surface area for particle capture. This may be overcome by operating the filter in an up-flow configuration, which has been shown to provide greater particle deposition (Chrysikopoulos and Syngouna, 2014). However, down-flow multimedia filters benefit from the use of both large and small media grains, using large grains of low density media and small grains of dense media. Such a design enables the backwash to stratify the filter bed keeping large grains at the top and small grains at the bottom; hence encouraging deep penetration of solids and improved removal performance with depth. This counters some of the operational problems associated with single media filters offering the opportunity for such filters to operate longer and at increased hydraulic loading therefore retaining more solids. In this research a quadruple media filter was studied consisting of layers of anthracite, flint, alumina and magnetite, moving from large to small grain size from top to bottom.

Previous studies involving granular media filters have investigated hydraulic loading rates (HLRs) up to 25 mh^{-1} (Williams et al., 2007; Li et al., 2012; Cleasby and Baumann, 1962; Suthaker et al., 1995), rates typical of rapid gravity filters. Pressure filters have the capacity to operate at a higher rate (Tobiason et al., 2011). However, there is a paucity of information on particle capture when pressure filters operate at high HLRs. Operating the filter at higher rates is a cost effective means to increase throughput for the same area of filter bed. The aim of this research was to therefore investigate the effect of high hydraulic loading rate on the solids removal efficiency of a quadruple media filter treating wastewater secondary effluent. The contribution of each media layer was evaluated and the change in treated water particle size distribution (PSD) was assessed through each media layer.

2. Materials and methods

2.1. Filtration tests

The investigation was carried out using a pilot plant located at a small sewage treatment works (STW) in the United Kingdom, filtering real secondary treated wastewater effluent. The STW treats 2500 m^3 d^{-1} of municipal wastewater using preliminary screening and grit removal, primary sedimentation, alum dosing, trickling filters and secondary sedimentation. Secondary effluent from the STWs discharge well was pumped to a mixed holding tank from where the feed was transferred to the filter rig (Fig. 1). The quadruple media filter pilot plant was adapted using the same media layers as used in a commercial filter system (FilterClear, Bluewater Bio, UK). For the purpose of this study, the media were separated into different columns and connected in series so that the effect of each layer could be isolated. In the pilot plant, transfer between the layers had a retention time of less than 2 min, and particle size analysis confirmed that particle characteristics were not changed during transfer from one filter layer to the next. Wastewater was pumped from a holding tank to the filter columns by a variable rate peristaltic pump (620 Industrial LoadSure, Watson Marlow, UK) through a flowmeter (SM6000, IMF Electronic Ltd, Germany). The filter rig consisted of four clear acrylic perspex columns of 700 mm height and 74 mm internal diameter. The columns were connected using PVC fittings and a clear PVC hose. Filter nozzles (Type KRI, KSHFisher, Germany) were fitted at the base of the columns to hold the filter media in place and evenly distribute the flow during the backwash cycle. The columns were connected so that the outlet of one column was fed into the inlet of the next.

Each column contained a different media at a depth of 100 mm. The media were anthracite (effective size, ES = 1.12 mm, uniformity coefficient, UC = 1.49, loose bed porosity, $\varepsilon_0 = 0.51$, sphericity, $\psi = 0.54$), flint (ES = 0.55 mm, UC = 1.42, $\varepsilon_0 = 0.52$, $\psi = 0.64$), alumina (ES = 0.58 mm, UC = 1.13, $\varepsilon_0 = 0.55$, $\psi = 0.63$) and magnetite (ES = 0.26 mm, UC = 1.54, $\varepsilon_0 = 0.47$, $\psi = 0.84$) respectively. A standard method was used to obtain the media effective size and uniformity coefficient (American Society for Testing and Materials (ASTM) C136-2006). The loose bed porosity ε_0 was determined by method ASTM C1252-2006 and the sphericity ψ was determined by calculations based on clean bed headloss measurement and the Kozeny-Carmen equation.

Online instruments for flow, pressure and turbidity were connected to the filter rig and the output analogue signals were logged into a laptop by an analogue-digital data logger (D-149, Dataq Instruments, UK). The columns were fitted with pressure transducers (PN2026, IMF Electronic Ltd, Germany) at the bottom and top of each media bed (100 mm apart) to measure the pressure drop across the filter bed. Sampling points were positioned at the influent and effluent to each column. The influent and effluent turbidity was monitored by probes placed in the influent holding tank and the effluent pipe (Turbi-Tech 2000LS and WaterWatch 2310, Partech, UK, respectively). The filter was run at a determined constant flow rate (from 5 to 60 mh^{-1}) for each filter run and grab samples were collected on an hourly basis for analysis. Each flow rate condition was run in triplicate. At the end of the filter run, the columns were backwashed individually by an air scour (2 min) followed by high rate (60 mh^{-1}) water wash (10 min) using the filtrate. As each filter column could be isolated, it was not possible for the different media layers to mix with one another during filter backwash.

2.2. Performance measurements

The total suspended solids (TSS) were determined from grab samples by gravimetric analysis Method 290D (APHA, 2005). Turbidity was measured in the laboratory using a turbidity meter (2100 Lab Turb, Hach, US). Zeta potential was measured by a zetasizer (Zetasizer Nano ZS, Malvern, UK). During sampling, the opening and closing of the sampling taps was carried out slowly to avoid hydraulic shocks in the system. The PSD of suspension particles was measured using a laser diffraction particle sizer (Spectrex PC-2200, Spectrex Corporation, California) within 30 min of sampling to minimize aggregation. The grab samples were diluted by a factor of 12 to reduce the effect of particle shielding at high concentrations.

2.3. Filtration models

Filtration was modelled using colloid filtration theory to show the effect of HLR on the retention of suspension particles by collectors, an approach used in drinking water filtration, but not to our knowledge in wastewater filtration. Filtration models have been defined assuming laminar flow conditions (Tobiason et al., 2011). To show that the filtration systems used in this work was operating