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Observations of rapid flow rate disturbances in drinking water filters and their effect on solids removal

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ABSTRACT: Rapidly fluctuating flow rates, known as surging, have been shown to produce poorer water quality from rapid gravity filtration. This paper compares observations of surging made at treatment plants in the UK with those reported in the USA. Two rapid filters were previously developed in the laboratory to study the impact of surging on filter performance. Head loss and turbidity removal were measured. The surges applied caused a deterioration in filtered water quality but unlike the previous work, filter performance was suppressed throughout the filter cycle and not just during the early stages. The surges applied here slowed the rate of head loss development in the filter, generating a longer filter run but at the expense of poorer quality water. The results suggest that surging flow similar to that found in full scale filters in the UK and US could have a significant effect on filter performance and may have implications for the removal of *Cryptosporidium* and *Giardia*. Recommendations are made on how to minimise the occurrence of surging in present and future water treatment plant designs.

INTRODUCTION

The presence of small but rapid fluctuations in the flow rates through rapid gravity filters was first identified by Baylis [1]. It was reported that poor solids removal from experimental filters was linked to continuous pressure fluctuations observed in the water piezometers used to record filter head loss. Baylis believed that these oscillating water levels in the piezometers, which he called surges, resulted from erratic fluctuations in the rate of flow through the filters. Measurements were subsequently taken from a range of pilot and full scale filters to identify the source of the fluctuations. Water piezometer tubes were connected within the filter media and at various points in the filtrate piping to measure the pressure fluctuations produced by the rapidly changing flows. Baylis found that continuously occurring pressure fluctuations from 10 to 100 mm in amplitude were common in gravity filtration [1]. These pressure fluctuations occurred at rates of up to 100 oscillations per minute. The source of these small but rapid changes in the flow was traced to the venturi flow meters and control valves in the filtrate piping. The pressure fluctuations measured within the filter media were found to be the result of turbulent velocity fluctuations at these constrictions in the flow in the filtrate piping. It was shown that the magnitude of the pressure fluctuations was proportional to the square of the velocity, as would be expected from turbulent losses. The observations also established that the magnitude of the pressure fluctuations increased with increasing loss of head through the filter. Baylis compared the performance of two pilot filters, only one of which was subject to surging [1]. He concluded that the surges contributed to more solids in the filtrate, but his filters were not identical and the results were not conclusive. From these observations, Baylis believed that surge amplitudes any greater than 1% of the head loss affect the efficiency of rapid filters [1].

Hudson compared the turbidity removal performance of declining rate and constant rate filtration and also observed pressure surges [2]. He noted that since the flow through conventional rapid gravity filters is laminar, any fluctuations observed in the head loss measurement must directly reflect fluctuations in the flow rate. The flow in the filtrate piping of rapid filters is not laminar and pressure fluctuations measured in this piping will be disproportionately larger than the disturbances in the flow rate. Hudson recognised that the surges observed by Baylis could originate at any high velocity zone such as a bend in the filtrate piping or a partly closed control valve. It was observed that the magnitude of surging decreased with time in the declining rate filters and this was attributed to the decrease in filtration rate in this method of operation. Like Baylis, Hudson found that the magnitude of the surges in the constant rate filter increased with rising loss of head. In his study, Hudson found that declining rate filtration produced better quality water than constant rate filtration. A 20% improvement in water quality over the 12-month study was believed to be the result of the smaller surges in the declining rate system [2].

Bernardo & Cleasby also compared constant and declining rate filtration [3]. They also concluded that the declining rate system produced a 30–60% lower average filtrate turbidity. Like Baylis and Hudson, the authors believed that the constant rate system may have been subject to small continuous flow rate fluctuations which caused the poorer quality filtrate [4].

Some initial observations on pressure fluctuations in the UK were reported previously [5]. These measurements using the filter head loss gauges indicated small but rapidly occurring fluctuations, in pressure in the filtrate piping. Surges up to 100 mm in magnitude at rates of up to 80 oscillations per minute were observed. The pressure fluctuations also increased with head loss similar to the findings of Baylis and Hudson [1,2].

It is well known that large step increases in the flow through filters causes short-term solids breakthrough with a reduction in head loss [6–9]. Cleasby *et al.* used controlled experiments and identified that single large flow rate increases produced a short-term deterioration in filtrate quality when applied to experimental rapid filters midway through the filter cycle [10]. It was found that previously captured deposits were scoured from the filter media by the increase in flow. The increase in flow was believed to create an increase in the hydraulic shear acting on the retained deposits causing some to detach. This resuspended material penetrated further into the bed with some breakthrough into the filtered water. In an attached discussion, Hudson commented on the difference between the flow rate increases applied by Cleasby *et al.* [10] and the surges described by Baylis [1]. Surges are momentary erratic fluctuations in flow rate occurring from 5 to 100 times a minute. These surges are present throughout the filter run and were small compared to the large single step increases applied by Cleasby *et al.* [10]. Hudson reported that surge amplitudes of 2–10% in the filtration rate were common in full scale rapid filters but that their effects had yet to be quantified [11].

Recent studies have identified that *Giardia*, *Cryptosporidium* oocysts and viruses can penetrate rapid gravity filtration and survive conventional disinfection [12–16]. Several studies have shown that *Giardia* and *Cryptosporidium* oocysts are common in surface waters and can be found in filtered drinking water [17–20]. The Oxford/Swindon outbreak in the UK illustrated that oocysts can appear in the filtered water supply without any indication of poor treatment performance [21]. It has been identified that even a small increase in filtered water turbidity can represent large numbers of particles [7,9]. It has been recommended as part of a multiple barrier approach to the prevention of outbreaks of illness that flow changes be minimised in rapid filters with the adoption of a 0.1 NTU filtered water standard to safeguard public water supplies from protozoans [22–25]. The presence of surges could be an important influence on filter performance. The previous paper reported the initial findings of this study [5]. This paper reports later detailed field measurements of the occurrence of surges and results from the laboratory investigation on their effect on the performance of rapid gravity filtration.

Surging at UK water treatment plants

Measurements of pressure fluctuations were made at local UK water treatment plants. Pressure measurements were limited to using the existing plant instrumentation. Plant A was designed to treat a maximum of 32 ML/day. The plant operated four constant rate rapid gravity filters of 50 m^2 surface area. At the

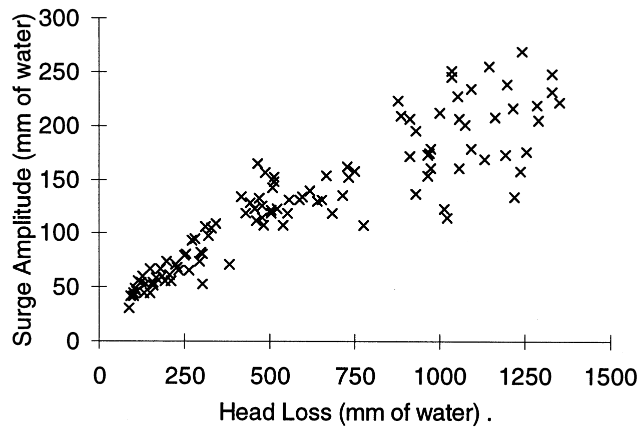

Fig. 1 Pressure fluctuations in the filtrate piping at plant A.

time of the measurements, the filters were operated at an approach velocity of 2.5 m/h. Approach velocities of 5–10 m/h are more typical of conventional rapid filtration. Head loss was recorded using pressure transducers fitted above the media surface and to the filtrate piping upstream from the flow control valves. The supervisory control and data acquisition (SCADA) system recorded the pressure drop once every 60 s. Filter head loss was presented as the average of 15 consecutive readings. An indication of the magnitude of surging present was given from the maximum and minimum values recorded during the 15 consecutive readings. Figure 1 illustrates the maximum fluctuation, in pressure drop recorded by the plant instruments every 15 min throughout the filter cycle. The data shown in Fig. 1 indicates continuous fluctuations in the flow rate throughout the filter cycle. These results are similar to Baylis' and Hudson's observations [1,2]. The magnitude of these pressure fluctuations also increased with rising loss of head across the filter media. At higher more typical filter loading rates the pressure fluctuations would be larger than observed here. No information regarding the frequency of these fluctuations can be given due to the limitations of the plant SCADA system.

Plant B was designed to treat a maximum of 140 ML/day. The plant operated 12 constant rate rapid gravity filters each of 67 m^2 surface area. The filters were operated at approach velocities of 4–7.25 m/h depending on demand. Filter head loss was recorded by pressure transducers fitted above the media and to the filtrate piping upstream of the control valves. The head loss was displayed continuously on analogue gauges. Surge amplitudes and rates of occurrence were recorded continuously throughout the filter cycle by visual observation of the gauges in a similar manner to the method used by Baylis [1]. Figure 2 illustrates the magnitude of the pressure fluctuations recorded. It can be seen that pressure fluctuations smaller than plant A but similar to those observed by Baylis and Hudson occurred [1,2]. The frequency of the pressure fluctuations were from 30 to 100 oscillations per minute throughout the filter

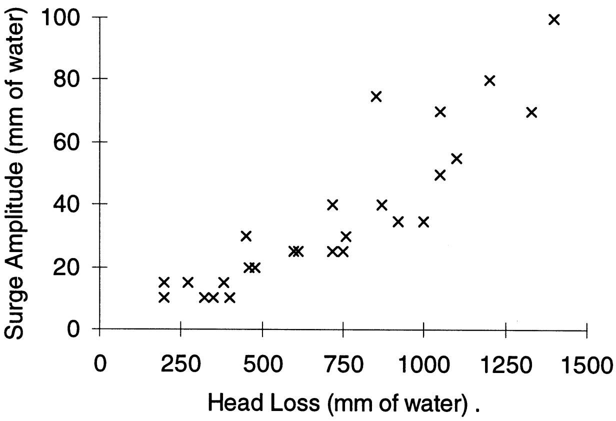

Fig. 2 Pressure fluctuations in the filtrate piping at plant B.

cycle. The magnitude of the surges as in plant A increased with rising loss of head across the filter media. In both Plant A and B, the pressure fluctuations were measured in the filtrate piping upstream of the flow control valves. The magnitude of the resultant fluctuations in pressure within the filter media are not known but are expected to be much smaller.

MATERIALS AND METHODS

Experimental apparatus

The apparatus used is shown in Fig. 3. Tanks used to store the raw water were fitted with stirrers to keep the test suspension thoroughly mixed. Immersion heaters were used to maintain a fixed operating temperature of 30 °C. The air temperature in the laboratory exhibited seasonal fluctuations which interfered with the early experimental control. An elevated water temperature of 30 °C was required to maintain good experimental control throughout the investigation. It should be noted that typical water temperatures at water treatment plants in the UK can range from 5 to 25 °C. At these lower temperatures the effect of the flow disturbances will be greater than reported here due to the greater water viscosity.

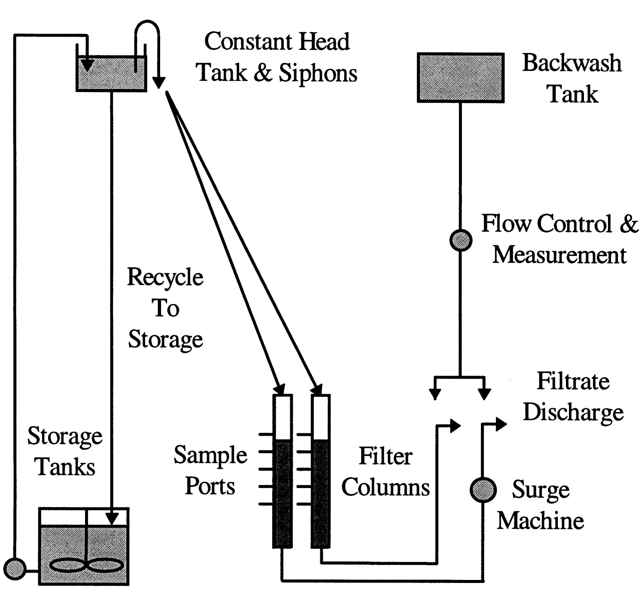

Fig. 3 Experimental apparatus used to investigate surging.

The suspension was pumped to a constant head tank where two siphons delivered identical constant flow rates to the filter columns. An approach velocity of 8.0 m/h was used to represent conventional rapid filtration loading. The filters were operated on a constant flow rate, rising head principle. That is to say the water level above the sand rose as the beds accumulated deposits, maintaining a constant flow rate. The filter columns were 1.5 m long and were constructed from 58 mm internal diameter perspex piping. The columns contained the sand beds supported on layers of graded gravel. Great care was taken to ensure that the beds contained identical sand mass and size distribution. The media used was Leighton Buzzard sand with a size range from 0.5 to 1.0 mm. Stevenson recommended the use of the hydraulic size in the specification of rapid filter media [26]. The hydraulic size was calculated to be 0.75 mm from sieve analysis. For comparison, the effective size and uniformity coefficient were found to be 0.62 mm and 1.27 mm, respectively. The sand beds were backwashed before each run using tap water at 20 °C to an expansion of 20%. The sand beds became size graded as a result, with 0.5 mm grains at the surface and 1.0 mm grains at the base. The beds were settled down after backwash, using an electric shaker, to identical depths of 600 mm each time. The filter columns were fitted with pressure ports above and below the beds and at depths of 15, 30, 50, 100 and 150 mm from the sand surface. Pressure was measured using manometric water piezometers connected to these ports. Drip sample ports were fitted to the columns above the sand and at depths of 50, 100, 200 and 400 mm from the surface for turbidity sampling. Sampling the suspension from within the filter bed required some method of withdrawing a representative sample of fluid without disturbing the bed deposits. Ideally, the point of withdrawal should be away from the filter walls to avoid the effects of the proximity of the wall on the media porosity. Secondly, the rate of sampling should be isokinetic to avoid scouring the deposits near the entrance to the sampling port. That is to say the velocity of the fluid entering the body of the sample port should be similar to the interstitial velocity within the filter pore spaces. Previous researchers have recognised that isokinetic sampling is an ideal that is difficult to achieve in filtration research and that a compromise is necessary in practical terms [27,28]. The drip ports used were constructed from 0.6 mm internal diameter steel needles inserted into the beds through septa similar to those used by previous researchers [29]. The ends of the needles were placed 15 mm into the bed to avoid the effects of the filter walls. To match the sample velocity in the needle to the fluid flow in the filter pores would require an impractical sampling rate of less than 5 mL/h. Samples were collected from the drip sample needles at a rate of 200 mL/h, similar to other workers [29]. This was deemed acceptable since previous work had shown that isokinetic sampling was not necessary with nonflocculated particles [28]. The control filter and fluctuating filter columns used in this study were sampled at identical sample flow rates for comparison. Turbidity was measured using a Hach Ratio turbidimeter, model XR. To prevent the formation of negative head within the bed the filters discharge from outlets set above the sand surface. Attached to the effluent piping of filter two is a motor driven pump designed to produce pressure fluctuations similar to those observed in the full scale plant.

Raw water preparation

1500 L of raw water were needed to complete each experimental run. The raw water was characterised to ensure reproducible filter performance. Several researchers have used polyvinyl chloride (PVC) powders dispersed in water [8]. The advantages of PVC powders are that they are easily dispersed in water and form stable suspensions. The PVC powder used was EVIPOL MP7057, supplied by European Vinyls Corporation (UK) Ltd (1 Kings Court, Manor Farm Road, Runcorn, WA7 1HR, UK). To produce a suspension of PVC particles of reproducible concentration and particle size distribution the raw water was prepared by adding batches of PVC powder to tap water and mixing for a short period in a high shear blender. The tap water used had a conductivity ranging from 500 to 700 microsiemens per centimetre and a pH of 7.0–8.0. The tap water contained 10–15 mg/L Mg^{2+} and 50–80 mg/L Ca^{2+}. The mixed suspension was allowed to settle in a beaker for 8 h to remove large particle sizes and the supernatant siphoned off. This supernatant was used to dose 1500 L of clean tap water to the required concentration in the storage tanks. This procedure was found to produce a stable raw water of repeatable concentration and particle size distribution. Particle size distribution analysis was conducted using a Coulter Laser Sizer (model LS130). The prepared raw water had a particle size distribution from 0.1 to 15 microns with a Mode diameter of 3.0 microns and a turbidity of 50 NTU. Further discussion of the experimental apparatus and materials used is reported elsewhere [30].

RESULTS AND DISCUSSION

Fixed amplitude pressure fluctuations of 100 mm were found to inhibit initial solids removal and slow the head loss development of experimental filters [5]. However, it is clear from the measurements taken at Plant A and B and from previously published findings that the size of the pressure fluctuations in full scale rapid filters increase with time as the filter accumulates solids [1,2]. At a constant rate of flow, the pressure drop will increase as deposits accumulate in the filter media. Thus for a given magnitude of fluctuation in the flow the magnitude of the fluctuation in pressure drop will increase as the filter accumulates deposits in the filter media. Increasing amplitude pressure fluctuations were thus applied to the experimental filters to reflect this observation. Control runs with no pressure fluctuations were conducted to ensure good reproducibility. Surging was then applied to filter two only. The pressure fluctuations applied to filter two were increased from an initial amplitude of 50 mm at the start of the run to 140 mm at the end as the filter accumulated deposits and head loss. The fluctuations were applied continuously throughout the filter cycle at a rate of 80 oscillations per minute based on the field observations. The effect of these pressure fluctuations on head loss and turbidity removal efficiency across the 600 mm of media are illustrated in Fig. 4 and Fig. 5. The head loss and turbidity removal efficiency are presented as the difference between filters in each run. This is calculated by subtracting the head loss or removal efficiency of the control filter one from filter two.

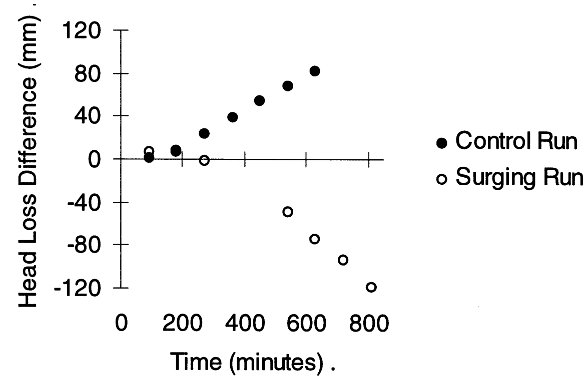

Fig. 4 Effect of surges on head loss development.

Figure 4 shows that filter two developed 80 mm more head loss than filter one during the control test run. This small inherent difference in performance was attributed to unavoidable variation in the manufacturing tolerance of the materials used in the construction of the two filters. This small difference

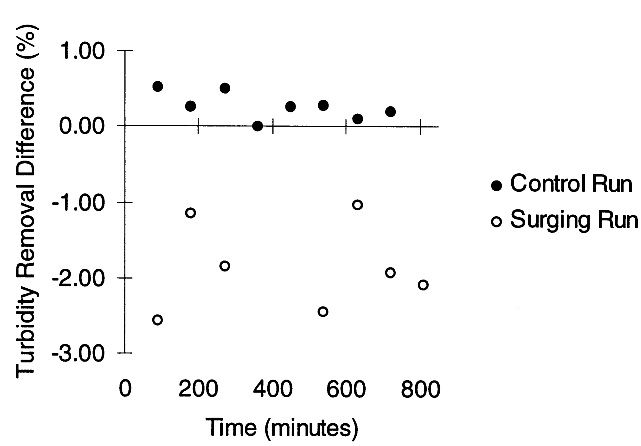

Fig. 5 Effect of surges on turbidity removal.

in performance was confirmed as reproducible by repeated control tests and is taken into consideration in the analysis of the results. The effect of the increasing amplitude pressure fluctuations was to slow the rate of head loss development in filter two such that filter two developed 120 mm less head loss than filter one during the surging test run. This is equivalent to 200 mm less head loss than the performance of filter two observed in the control runs. The lag in head loss development in the surging filter is explained by the turbidity removal results.

It can be seen in Fig. 5 that filter two performed marginally better than filter one in turbidity removal efficiency throughout the control test run. The effect of the increasing amplitude pressure fluctuations was to cause a lag in the turbidity removal efficiency of filter two of 1–3% during surging. This poorer particle removal produced the slower rate of head loss development shown in Fig. 4. The fixed amplitude pressure fluctuations reported previously also caused a lag in turbidity removal efficiency during the early stages of the filter cycle [5]. This deficit was recovered by the end of the filter run. The increasing amplitude pressure fluctuations reported here caused a smaller deficit in turbidity removal efficiency that was present throughout the filter cycle. The surging filter did not recover and removal remained 1–3% poorer at the end of the test run.

The pressure fluctuations generated within the filter media by the increasing amplitude fluctuations applied to filter two were recorded. It was noted that the magnitude of the pressure fluctuations at a depth of 15 mm from the surface of the media ranged from 1 mm at the start of the filter cycle to 4 mm at the end. The magnitude of the fluctuations generated within the filter media by the surges are much smaller. The frequency of occurrence was unaffected. The pressure fluctuations observed within the filter media in this study are believed to reflect the presence of small continuously occurring fluctuations in the interstitial velocity. These fluctuations in velocity were believed to create small continuous changes in the hydraulic shear acting on suspended particles approaching the sand grain surfaces. These fluctuations in hydraulic shear then inhibit the rate of particle attachment throughout the filter cycle. The presence of such fluctuations within the filter media of full scale rapid filters will similarly reduce particle capture. Indeed, it seems likely that the influence of flow disturbances will be more significant in full scale plant since flocculated particles will be more susceptible to fluid shear that the nonflocculated PVC particles used in this study. Surging may therefore hinder the attainment of a 0.1 NTU filtered water quality standard. The avoidance of high velocity zones in the filtrate piping will serve to reduce the occurrence of surging. The adoption of a declining rate filtration method of filter control may help reduce the magnitude of surges.

CONCLUSIONS AND RECOMMENDATIONS

- Evidence of small continuously occurring pressure fluctuations can be found in modern rapid gravity filters.
- The pressure fluctuations within the filtrate piping were observed to increase with rising head loss similar to previous authors' findings.
- Surges of this nature caused a deterioration in particle removal performance and a reduced rate of head loss development in laboratory filters.
- The amplitude of the resultant pressure fluctuations within the filter media was observed to be much smaller than applied in the filtrate piping.
- The pressure fluctuations within the filter media were sufficient to inhibit particle attachment throughout the filter cycle.
- The pressure fluctuations within the filter media were believed to reflect small continuously occurring fluctuations in the interstitial velocity.
- These fluctuations in interstitial velocity produced fluctuations in hydraulic shear reducing particle capture.
- Reducing or eliminating the presence of surges will contribute to the attainment of a 0.1 NTU filtered water quality standard to guard against disinfection resistant pathogens such as *Cryptosporidium*.
- A comprehensive survey of surging in modern rapid gravity filters is needed to assess the extent of the risk. This should include measurements within the filter media since it is here that particle attachment is affected.
- A pilot plant study of the effect of surges on particle and *Cryptosporidium* removal using flocculated natural water and field operating conditions would be useful in assessing the risk to public water supplies.

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