The disturbance of sand filter supporting layers by air scouring

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Abstract

This paper deals with the backwashing of rapid sand filters and in particular with the method whereby the filter bed is subjected to a period of scouring with air alone before the impurities are flushed from the bed with a low velocity backwash.

It was found that this widely used method has the potential to disturb the gravel layers on which the sand is supported if the air scour rate exceeds a certain value. Experimental work is reported which indicates when, how and under which circumstances the gravel particles intermix with the sand. Preliminary design parameters are proposed to prevent the intermixing of sand and gravel.

The serious consequences of this intermixing are outlined and a few of the many possible solutions are briefly evaluated.

Introduction

Effective cleaning of the filter media in a rapid sand filter at the end of every filter run is not only the most important prerequisite for a long and trouble-free filter life, but probably also one of the most difficult aims to achieve consistently. Without effective cleaning the residual floc or impurities retained by the filter bed after a backwash cycle steadily increases to the point of mudball formation, filter cracks, dead filter patches and other related filter ailments.

It has been shown (Amirtharajah, 1978) that backwashing with water alone exerts maximum hydrodynamic shear on the media grains at a bed expansion of 40 – 50%, but that even then the floc detachment forces on the media grains are not sufficient for the removal of sticky, heavy deposits. In South Africa, when sticky, heavy deposits result from treating turbid inland waters, often with the aid of a polyelectrolyte, it follows that backwash with water alone cannot clean the media effectively and consistently. The use of a backwash auxiliary thus becomes imperative.

The use of air as a backwash auxiliary is common in South Africa. (The use of surface wash, the other popular option, is largely confined to the USA). Air can be applied either alone, or simultaneously with water. It has been conclusively proved (Cleasby and Lorence, 1978) that the latter combination is the most effective of the two in terms of media cleansing. Two factors have however limited its widespread use. Firstly it has much greater potential to disturb the filter media supporting layers when using stratified filter beds, which is a serious consequence as it leads to sand leakage into the underdrain system, clogged filter nozzles, uneven distribution of water and air and further related problems. Secondly, the greater agitation caused by this air scouring mode suspends a significant portion of the media into the water layer overlying the filter bed. The possibility of media being washed into the washwater trough is thus a very real one when using air and water simultaneously, particularly if dual media filtration is employed e.g. sand/anthracite. These reasons probably contributed to the fact that a great number of water treatment plants in South Africa employ the option where the air is used separately, to be followed by a low velocity backwash.

During 1980 serious gravel layer disturbance was observed at a newly commissioned water treatment plant where air alone was used as a backwash auxiliary. The underdrain and backwash systems were both well established and reputable designs of which many are operational in South Africa and where the disturbance of the gravel layers is an unknown phenomenon. The only difference was that the client requested an air scour rate of 15,0 mm/s, to which all parties involved agreed at that time. This rate is much higher than the normal 6,0 – 7,5 mm/s used for this particular filtration system. This experience showed that gravel disturbance can be caused even by air alone if the air scour is increased beyond a certain critical rate which appeared to be somewhere between 7,5 mm/s and 15,0 mm/s.

The remainder of this paper is a summary of an investigation (Haarhoff, 1982) which was undertaken after this experience to determine the exact cause and mechanism of the gravel disturbance and to establish the critical air scour rate above which the gravel would be disturbed for this particular filtration system.

The air scour cycle

A rapid sand filter basically consists of two compartments, one on top of the other. The top compartment, the filter bay, retains the filter media whereas the bottom compartment, the underfloor volume, is an empty compartment directly below the filter bay. The underfloor volume not only collects the filtrate during filtration, but also distributes the washwater and air evenly under the filter bay during backwashing. These two compartments are divided by the filter floor and the filter nozzles, which are screwed into the filter floor, allow the passage of water and air between the filter bay and the underfloor volume.

At the end of a filter run, water is drained from the filter bay until only approximately 100 mm of water is left above the top of the filter media. At this stage the underfloor volume is completely filled with water and the supply pipework from the air blower, which joins onto the underfloor volume, may be partially filled with water.

The air scour cycle is initiated when the blower is started. The air in the blower pipework compresses and simultaneously water is displaced from the blower pipework and the underfloor

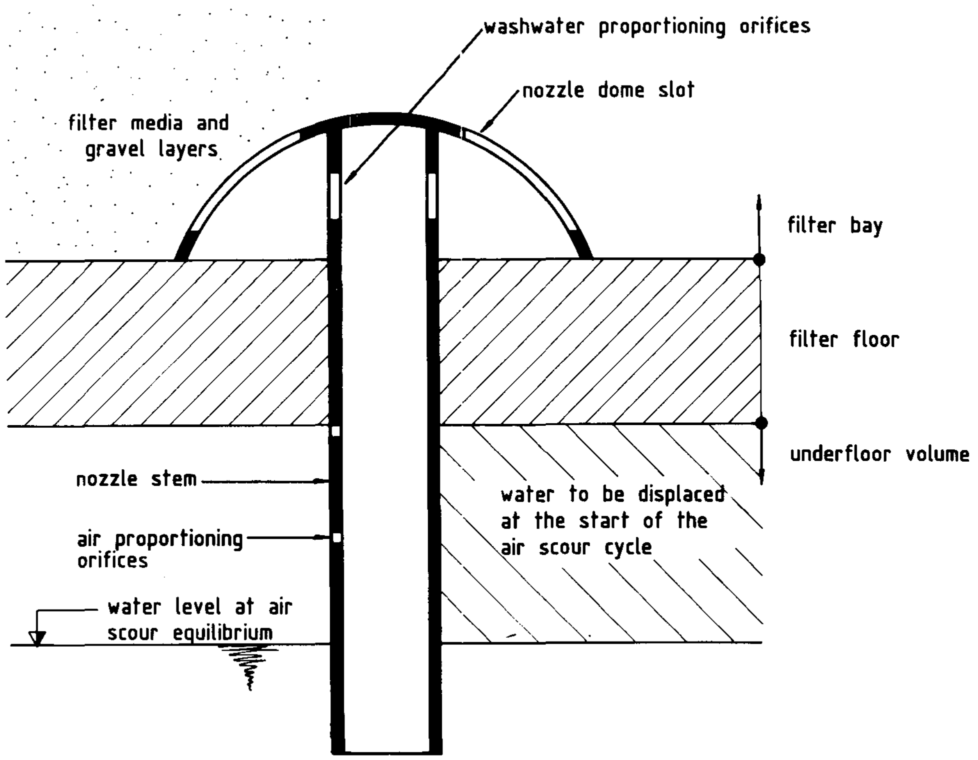

Figure 1
Cross-section through a typical filter nozzle

volume. The displaced water escapes from the underfloor volume via the filter nozzles into the filter bay. During this initial water displacement phase the filter bed is thus subjected to a backwash with water. This backwash rate is slightly less than the air scour rate due to the fact that the underfloor pressure is higher than atmospheric pressure – the air is thus somewhat compressed. (Air scour rates are expressed as free air at STP).

The water level in the underfloor volume is steadily depressed until the air reaches the air proportioning orifices in the nozzle stems. (Figure 1). At this point air starts to discharge through the nozzles into the filter bay. As the equilibrium water level in the underfloor volume is 30 – 50 mm below these orifices, it means that a certain amount of water is displaced *after* air starts to bubble through the filter bed. The consequence is that a short period exists during which water and air are simultaneously discharged through the filter nozzles.

After the water level in the underfloor volume has attained equilibrium, air alone is discharged through the nozzles until the end of the air scour cycle. At the start of air discharge the air travels as discrete bubbles through a mixture of water and sand. With time free water is gradually displaced from this mixture causing the sand to compact slightly. Because of this compaction the air, after a minute or two, travels along fixed channels formed in the sand.

There are thus three distinctly different modes of agitation during an air scour cycle, although the system is designed to scour with air alone. Initially there is a backwash with displaced water, then a brief period of simultaneous air and water, finally followed by a period of air scour alone.

Experimental observations on the air scour cycle

An experiment was conducted to ascertain during which of the three phases, identified in the preceding section, disturbance of the gravel supporting layers takes place.

Apparatus

A transparent PERSPEX tube, 194 mm ID and 1 500 mm long, was mounted vertically on a base plate with a single nozzle in the centre of the base. The base plate was mounted onto a 400 mm x 400 mm x 500 mm deep box into which water and/or air could be fed. Air and water flows were metered and the air and water rates could be regulated by hand throttling of the feed valves. Washwater was discharged through a chute at the top of the tube. The filter nozzle used was a standard nozzle designed for an air scour rate of 15,0 mm/s and a washwater rate of 9,8 mm/s. These nozzles are installed in actual plants at a density of 31 nozzles per m^2. The equivalent density in the experimental filter was 34 nozzles per m^2.

Filter media and supporting layers

The filter media was siliceous sand with a specific gravity of 2,64. The grain size fell within the 0,50 – 1,18 mm bracket with an effective size of 0,63 mm and a uniformity coefficient of 1,41. This sand started to fluidize at a backwash velocity of 7,25 mm/s at a water temperature of 11,5 – 13,5 °C. A sand layer of 450 mm thickness was used in the experimental filter. In an actual filter this sand layer would be typically 700 – 900 mm thick.

Two gravel supporting layers were used. The top layer consisted of flaky shale particles which passed a 4,75 mm sieve, but were retained on a 2,36 mm sieve. A layer of 100 mm was used in the experimental filter. The coarser bottom layer, 130 mm thick, consisted of those particles passing a 13,2 mm sieve but retained on a 9,5 mm sieve. In actual plants a layer thickness of 150 mm is generally used with 6,7 – 13,2 mm particles.

Experimental procedure

The three phases of the air scour cycle were each simulated in turn.

The "water alone" – phase was simulated by increasing the backwash rate very slowly from 0 mm/s to 20 mm/s. (At a 15 mm/s air scour rate water is displaced at a rate of 12 – 13 mm/s due to the compression of the air mentioned before. The experimental values extended to well beyond 13 mm/s).

The "air and water simultaneously" – phase was simulated by discharging air at rates between 10 and 30 mm/s into the underfloor volume which was completely filled with water. Observations were only confined to the very brief period (1 – 2 s) during which a mixture of air and water is discharged through the nozzles. After every run the air supply was shut off and water allowed to seep back into the underfloor volume. The filter bed was not rebuilt after every run.

The "air alone" – phase was simulated by very slowly increasing the air scour rate to minimise the effect of the water being displaced. The rate was increased from 10 to 90 mm/s.

In all three cases careful observations of the supporting layers were made through the transparent side of the filter tube.

Results

No movement or disturbance of the gravel could be observed for any of the washwater rates simulated.

The simulation of air and water simultaneously, however, did show a disturbance of the supporting gravel at all the rates applied. As the first burst of air hit the bed, gravel particles were flung up into the sand above it.

The simulation of air alone did not show up any disturbance of the supporting gravel. The media gradually compacted to such an extent that rates eventually as high as 90 mm/s could not disturb the gravel.

Conclusion on the air scour cycle

This experiment indicated that the bulk of the damage to the gravel layers was done during the short period when water and air were simultaneously discharged. From the results obtained it seemed as if all the damage was done only during this phase, but a weakness in the experimental apparatus must be pointed out. The side of the filter was 97 mm away from the centre of the nozzle and one would expect the damage to be more severe directly above the nozzle. If this is the case, it could well be that smaller disturbances were caused during the first or the third phases of the air scour cycle, but that it could not be observed at the side of the filter. Even if this were so, the conclusion that the bulk of the damage was done during the second phase would remain valid.

Nature of the gravel disturbance

Having determined at what point in time the gravel was disturbed, the investigation proceeded to experimentally determine the nature of the disturbance.

Apparatus

For this determination a rectangular box filter was used, 180 mm wide, 1 440 mm long and 1 200 mm high. It had a single row of eight filter nozzles in the base resulting in a nozzle density of 31 nozzles per m^2. The one side of the filter bay was transparent so that visual observations of the media movement inside could be made. Nozzles, similar to the type used in the previous experiment, were screwed into a horizontally mounted transparent pipe, 100 mm ID, which constituted the underfloor volume. A schematic layout is shown in Figure 2.

The same sand and gravel as described in the previous section was used, with the exception that the layer thicknesses were, starting from the bottom, 60 mm, 60 mm and 600 mm respectively, the thinner layers to amplify any problems of gravel disturbance.

Experimental procedure

Twelve consecutive air scour cycles were applied at an air scour rate of 14,2 mm/s, it being close to the rate of 15 mm/s which was known to have caused gravel disturbance.

Before every run the bed was backwashed for approximately

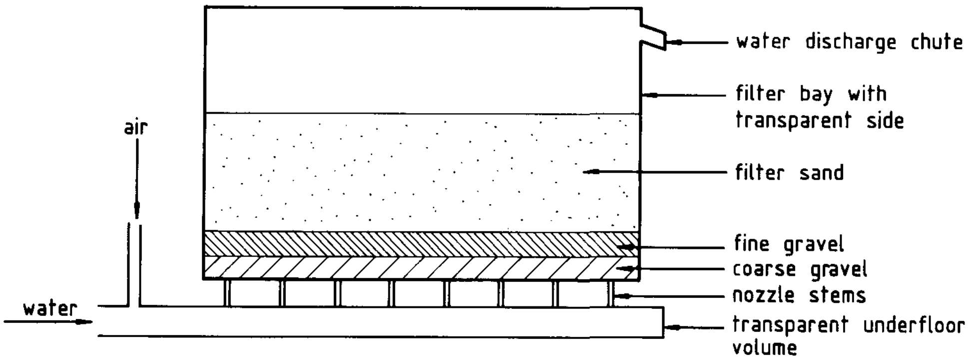

Figure 2
Schematic layout of experimental laboratory filter

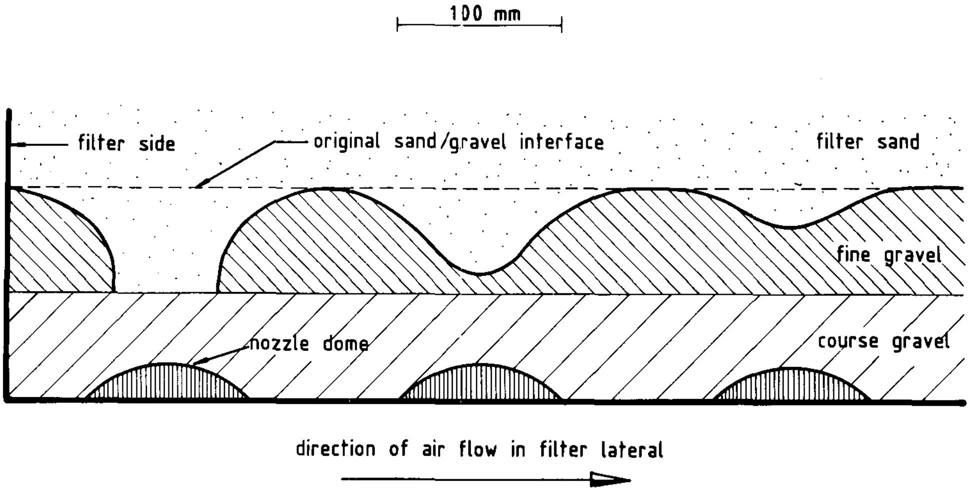

Figure 3
Cross-section through filter media and gravel supporting layers after twelve air scour cycles at an air scour rate of 14,2 mm/s

one minute at a rate just sufficient to fluidize the sand. After the backwash was turned off, air scour at a rate of 14,2 mm/s was applied until the water level in the underfloor volume had stabilised. The air was then turned off and water allowed to seep back into the underfloor volume.

After this cycle was repeated 12 times, the filter bed was carefully excavated down to the filter floor, and measurements were taken as the excavation proceeded.

Results

The gravel layers above the four nozzles furthest away from the inlet end showed no signs of disturbance. Above the fourth nozzle from the inlet end minute damage to the fine gravel was observed, whereas damage above the first three nozzles was serious and very obvious. No movement of coarse gravel particles could be observed. A cross-section of the gravel layers as found upon exavation is shown in Figure 3.

Conclusions on the gravel disturbance

The following may be concluded from Figure 3 in combination with the observations made at the side of the filter:

- The disturbance of the gravel layer starts at the sand/gravel interface.
- During the start of every air scour cycle the first burst of air to enter the filter bay propels a layer of fine gravel particles into the sand overlying it. The void left in the gravel layer is taken up by sand. In this manner the gravel is eroded away by an inverted sand cone steadily progressing towards the nozzles.
- After the fine gravel layer is eroded away, the sand travels freely into the much larger voids of the next gravel layer during filtration which is the onset of sand leakage into the underfloor volume, partially clogged nozzles, dead filter patches, etc.
- The number of gravel particles propelled into the bed during every air scour cycle, is dependent on the magnitude of the air burst through every nozzle. It will be explained in a later paragraph that the air burst through the first nozzle is indeed the most violent and thereafter it rapidly decreases further down the filter lateral. The vertical gravel erosion rate is in fact approximately 8 mm per cycle above the first nozzle, 4 mm per cycle above the second nozzle, 2 mm per cycle above the third, virtually zero above the fourth and thereafter zero.
- If it is considered that a rapid sand filter is backwashed some 200 times per year, it follows that an erosion rate of as low as 0,5 mm per cycle will puncture the standard 100 mm layer of fine gravel after a year. No gravel disturbance whatsoever is thus a prerequisite for a filter bed to be in a good condition after many years of operation.

Dynamics of air flow

A striking feature of Figure 3 is the rapidity with which the gravel disturbance diminishes, seen from the filter lateral inlet end. At the fullscale plant where the gravel disturbance was experienced, a similar phenomenon was observed. All the damage seemed to be concentrated in a narrow 1 m strip alongside the air header channel. This was determined by digging a number of trial pits down to the gravel layers. At this particular plant there were 26 filter nozzles to a lateral.

The first possibility that was considered was whether the air could momentarily uncover the bottom of the filter nozzle stem. The construction of a filter nozzle is such that two sets of orifices are provided. A small set of orifices is provided in the side of the nozzle stem for regulating the air. A larger set is provided, usually under the nozzle dome, for regulating washwater distribution. Figure 1 shows a cross-section through a typical nozzle.

Air thus enters the nozzle through the side of the stem while the bottom of the stem is immersed in water. Washwater flows mainly through the bottom of the stem. Due to the large difference in viscosity between water and air, the water orifices are considerably larger than the air orifices. Once the air has passed through the air orifices, the water orifices offer almost no resistance to the air. It follows that if air could enter some of the nozzles through the bottom of the stem, it would encounter almost no resistance at all and this would lead to a tremendous burst of air through those nozzles and a most uneven air distribution. The possibility of this happening was investigated experimentally.

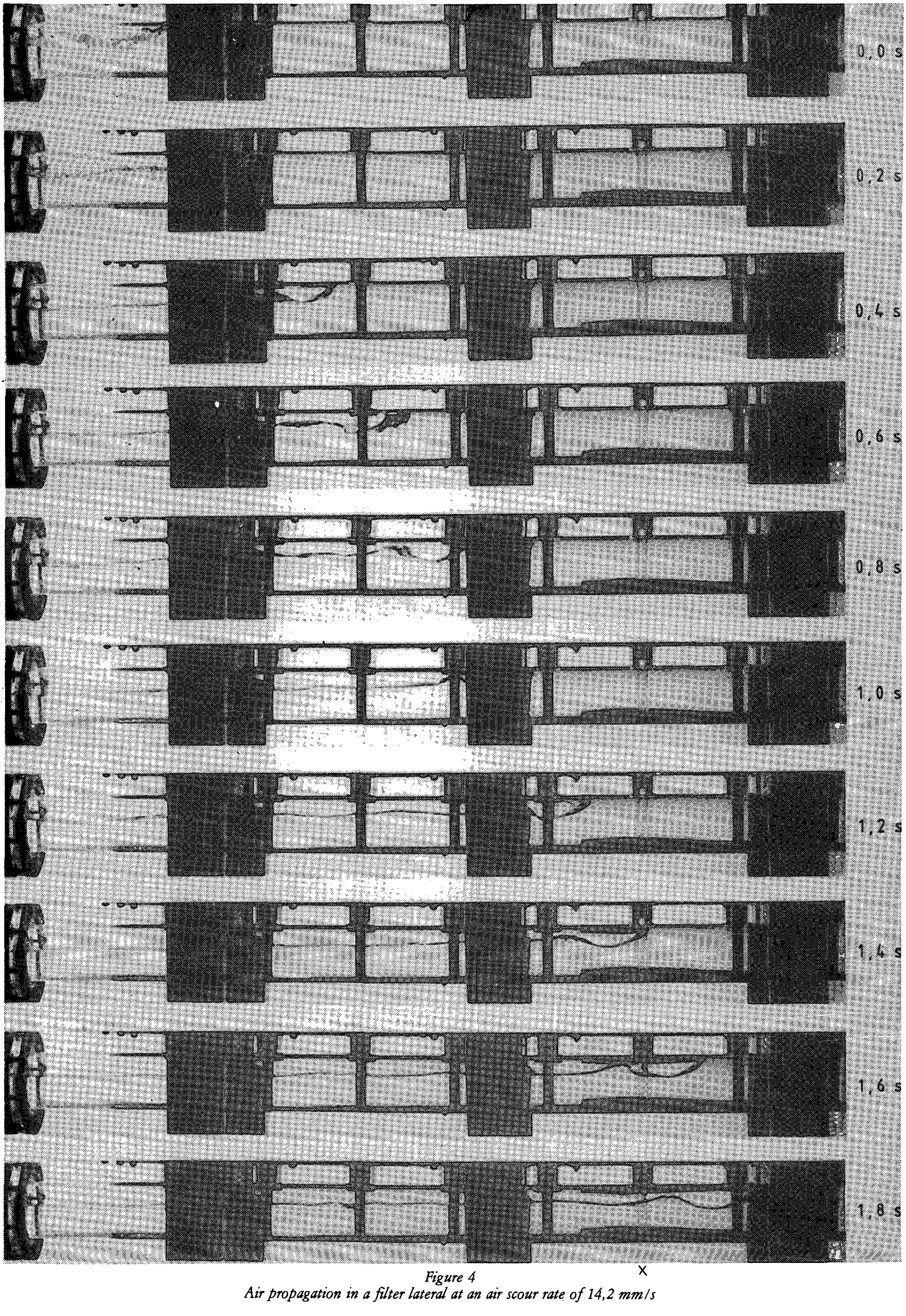

Figure 4
Air propagation in a filter lateral at an air scour rate of 14,2 mm/s

Experimental procedure and results

The filter with the eight nozzles, shown in Figure 2, was used with the same media and nozzles as before. Air was allowed into the transparent filter underfloor volume at an equivalent air scour rate of 14,2 mm/s. The actual air flow was thus 220 ℓ/min free air. The propagation of the air into the lateral was photographed at 5 frames per second with a camera fitted with a motor drive. A typical series of 10 photographs is shown as Figure 4. The time elapsed in seconds is shown in the righthand margin. One of the nozzles had a transparent stem and can be seen towards the right of the photograph.

Conclusions on dynamics of air flow

The following conclusions can be drawn from Figure 4.

- The speed of the air front is approximately 1,0 m/s as it passes the first nozzle and has dropped to approximate 0,6 m/s as it passes the sixth nozzle. (The sixth nozzle stem is transparent and marked with a cross at the bottom of Figure 4).
- The maximum depression of the water level by the incoming air was approximately 40 mm, which is much less than the 87 mm required to uncover the bottom ends of these particular nozzles. (This experiment was repeated at air scour rates of up to 40 mm/s and never were the bottom ends of any stems in any danger of being uncovered by the air).
- In the case of these particular nozzles, there were two air orifices, the one at the same level as the soffit of the filter lateral and the other 25 mm below the first. The first rush of air thus uncovered the two air orifices simultaneously.

The results of this experiment thus ruled out the possibility of the bottoms of the nozzle stems being uncovered. Another explanation had to be sought for the selective violent burst of air through the first few nozzles.

Theoretical headloss at the air orifices during the displacement of water

The moment before the first air reaches the nozzle stem, water only is being displaced through the nozzle. The headloss which exists across the air orifices during water displacement is thus also the headloss which governs the initial air burst through the nozzle.

This headloss can be calculated as the sum of the entrance loss at the bottom end of the nozzle stem and the friction loss of the water travelling up the stem. The fraction of the water entering the stem through the air orifices first needs to be calculated, as only the remainder of the water flows through the bottom end of the stem. The flow pattern in the nozzle stem is shown in Figure 5.

These calculations were carried out on four commercially available filter nozzles which are all used with the same underfloor system. The calculated headlosses from the bottom of the stems to the air orifices were then compared with the total headlosses measured experimentally across the filter nozzles. This fraction was found to be surprisingly high, ranging from 23 – 45%. De Lathouder (1961) made similar calculations and measurements on an entirely different type of nozzle and came to a percentage of the entrance loss at the bottom end alone of 26%. The internal stem diameter of the nozzles tested was 14 mm, which is within the range of commonly available nozzles. Six random nozzle types were analysed in a previous study (De Lathouder, 1961) and internal stem diameters of 13, 14, 15, 15, 16 and 19 mm were found respectively.

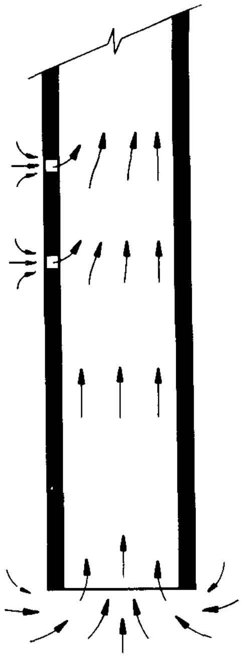

Figure 5
Flow pattern in a typical filter nozzle stem during water discharge

Estimation of the intital air burst

Under normal air scour conditions the headloss across the air orifices is typically 30 – 50 mm. Under the conditions just described in the previous paragraph the headloss during water displacement at the air orifices rises to much higher values. When air is introduced into the underfloor volume at a design air scour rate of 15 mm/s, the water being displaced causes a calculated headloss of approximately 500 mm from the bottom of the stem to the air orifices, this being ten times or more of the headloss at air scour equilibrium.

As discharge is approximately a function of the square root of the differential head, air flow through the first few nozzles which are uncovered by the air will be 3 – 4 times the equilibrium flow rate. For the particular nozzles used the air orifices were calibrated and using the exact relationships derived, it was calculated that these nozzles initially overdischarged 4,3 times!

This explains why the disturbance of the gravel diminishes so rapidly as the air travels down the lateral. After the tremendous gulp of air by the first nozzle, so much less air remains to displace the remainder of the water. After a smaller, but nevertheless greater than normal gulp of air by the second nozzle, the water displacement rate drops even more, *et cetera.* By following this reasoning it can be deduced that the magnitude of the air burst through the first nozzle is unaffected by the number of nozzles per lateral, the volume of the air cushion or the number of air entry points into the underfloor volume. The number of nozzles discharging more air than they should may be affected, but not the air discharge through the first nozzle.

This is a useful conclusion, as it means that a filter with one nozzle similar to the experimental one previously described, always must simulate the first nozzle of a row of nozzles. The worst affected nozzle of a large filter floor can thus be simulated by an extremely simple test filter.

The critical air scour rate

Experimental procedure

The box filter with the eight nozzles shown in Figure 2 was used, together with exactly the same media and supporting layers as before. Air was introduced at different rates and the sand/gravel interface directly above the first nozzle was closely observed through the transparent side of the filter.

Results

At an equivalent air scour rate of 4,6 mm/s, no movement of the gravel was observed as the first air was discharged through the first nozzle. With the next run an equivalent air scour rate of 8,7 mm/s was applied and a few gravel particles at the top of the fine gravel layer were just lifted into the sand above as the first burst of air rose through the bed. At other higher rates of 12,3 mm/s and 14,2 mm/s, the gravel displacement was much more obvious as little clusters of particles were flung from the gravel layer into the filter sand.

From the above results it can be deduced that an air scour rate of 8,7 mm/s is at or just above the onset of gravel disturbance. The word of caution mentioned before is repeated, namely that what happened at the transparent side of the filter is not necessarily what happened directly above the nozzle, as the observation plane was 90 mm away from the nozzle centres. It could thus be that the damage to the gravel layer starts at a lower air scour rate. This phenomenon could, and should be further investigated with equipment designed to allow observation of the media directly on the centre line of the nozzles.

The tendency of a gravel particle to move is not only related to the propelling force from below exerted by the air, but also to the degree of restriction offered by the sand overlying it. It is intuitively felt that the restrictive force of the sand will greatly diminish as soon as the sand starts to fluidize. If this theory is correct, it could be a useful tool to predict the air scour rate at which gravel disturbance becomes a real danger.

For the above experimental system, it was calculated that an air scour rate of 8,7 mm/s initially displaces water from the underfloor volume at an equivalent backwash rate of 7,6 mm/s. (The water displacement rate is lower than the air scour rate due to the high initial underfloor pressure which compresses the air somewhat). This water displacement rate is just above the sand fluidization rate of 7,25 mm/s. The theory advanced in the preceding paragraph thus accounts for the experimentally determined critical air scour rate of 8,7 mm/s.

If this theory can be conclusively proved, it means that a fine sand with a low fluidization point may have a lower critical air scour rate than a coarse sand with a higher fluidization point. It also follows that, should this be correct, that the critical air scour rate will be temperature sensitive, due to the fact that colder water will fluidize the same sand more easily than warmer water. It is strongly recommended that further research is undertaken with a variety of sands and gravels to test the general validity of this theory.

Possible solutions to the problem of gravel disturbance

A number of means to avoid gravel disturbance have been proposed and tried, of which Haarhoff (1982) quoted ten examples. Only the four most practical alternatives will be discussed.

Abolition of the sand supporting layers

If the slots in the nozzle domes were narrower than the diameter of the finest sand grains, the sand could be supported directly on the nozzle domes and the filter floor without fear of sand leaking through the nozzle domes into the underfloor volume. This is a neat solution which has in fact been extensively tried in South Africa.

There are practical disadvantages which could lead to the destruction of the filter floor if very special precautions are not taken. Most important of these is the fact that any particle that may enter the underfloor volume, will most likely be scoured into a nozzle during backwashing. All but the smallest particles will be trapped in the nozzle dome or become wedged in the dome slots. Nozzle domes could eventually become clogged to such an extent that the underfloor pressure exerts an upward force which exceeds the structural strength of the filter floor.

For a system without supporting layers it is a prerequisite to painstakingly clean out the underfloor volume after construction to remove *all* debris which may have accumulated. Furthermore the backwash and blower systems must be so designed as to avoid any solid matter from being drawn into the underfloor volume via the pumps or blowers.

A way of avoiding particles that do enter the underfloor volume from being scoured into the nozzles, is to provide a deep (>800 mm) sump as the underfloor volume. This will cause very low velocities in the sump during backwash so that the particles entering the underfloor volume will stand a good chance of settling out on the sump floor rather than being scoured upwards into the nozzle domes.

Keeping the design air scour rate below the critical value

In the preceding paragraphs it was shown that the gravel is only disturbed if a certain air scour rate is exceeded. Unless it can conclusively be proved that this rate is not sufficient for floc detachment, it is strongly recommended that an air scour rate below this critical value is selected, whatever the critical rate may be for a particular filtration plant. If the rate must necessarily exceed the critical rate, careful attention should be paid to keep the gravel from intermixing with the sand.

Using a reduced air scour rate at the start of the air scour cycle

A technique which is known to have been used at at least three water purification plants in South Africa, is to apply a reduced air scour rate for the first 30 – 60 s after the blowers have been started. Water is thus displaced from the underfloor volume by the low air rate without fluidizing the sand above the gravel. After the air has reached all the nozzles, the air rate is stepped up to the full design rate. In practice this is done by initially wasting approximately 50 % of the air through a relief valve on the blower pipework. After the preset time a timer closes this valve automatically.

There is however a disadvantage to this system which could be serious if it is not used with care. The effectiveness of air scour rapidly decreases with time during an air scour cycle. The most abrasion is caused as the first wave of air breaks through the bed.

As the bed thereafter compacts, the relative movement of particles decreases until it virtually ceases after 1 – 2 min, with the exception of the top 100 mm of the sand bed. (This is the reason why an air scour cycle of longer than 3 min is of little, if any value. It also explains the superiority of air together with water as a backwash auxiliary, where the water prevents the sand from compacting, thus allowing the air to maintain its maximum effect throughout the air scouring cycle).

If the low initial air scour rate carries on for longer than absolutely necessary, the bed starts to compact. By the time the full air rate is applied, the partially compacted sand prohibits the air from having maximum scouring effect.

When using this system, it is thus imperative to bleed off just enough air to keep the sand from fluidizing. Even then the relief valve must be closed immediately after the air has reached all the nozzles.

Double reverse gravel grading

This system was originally investigated (Baylis, 1959) as a means of preventing gravel disturbance during highrate backwash.

On top of the normal gravel supporting layers a few more gravel layers are added, becoming coarser to the top. Although the sand travels into the voids of these coarser layers, the combination of gravel and sand is not fluidized during water displacement and thus weighs the fine gravel layer sufficient down to inhibit gravel particle movement.

It was reported (Cleasby *et al*, 1975) that this system showed promise for holding the gravel down during simultaneous air and water backwash. If it proves successful with simultaneous air and water flow, it should also be suitable for the initial period when using air alone.

Final conclusion

The use of air scour in rapid sand filtration, prior to backwashing, has the potential of disturbing the supporting gravel layers unless certain precautions are taken; the most important of which is to restrict the initial air flow rate. In this study on a particular system commonly used in South Africa, the critical air scour rate was found to be approximately 8 mm/s under specific conditions.

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