FILTER BACKWASHING MECHANISMS

by

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ABSTRACT

An investigation of filter backwashing mechanisms was undertaken. High speed video recording equipment, operating at 200 frames/s, in conjunction with a rigid endoscope (borescope) has been used to obtain detailed visual information from inside the filter bed during backwash. In addition, experimental measurements of mass balance and backwash water turbidity have provided efficiency information.

Experiments were performed using standard filter sand, either clean or clogged with a suspension of kaolin clay, or kaolin clay flocculated with alum and polymer in London tap water. Backwashing with water or water and air scour was recorded on video for subsequent analysis. A total of 30 experiments were performed backwashing with water only and 38 using combined air and water wash of the clogged bed.

Using the XY Coordinator and a PC velocities of the sand grains were obtained from the video tapes for different backwash regimes.

The results indicate that the majority of detachment is due to the fluid shear forces acting on deposits on the grain surfaces, particularly when a water only wash is employed. Kaolin and flocculated kaolin deposits are easily detached without fluidising the bed, but some remain trapped in areas where there is no flow, or, where the shear forces are insufficient for detachment. Fluidisation serves: (i) to mobilise grains and expose new faces to the shearing effects of the flow, and (ii) to allow flushing out of the resuspended deposits. Grain collisions and abrasion do take place, particularly as the bed undergoes expansion, but these were not the major cause of deposit detachment in the experiments described.

When simultaneous air and subfluidising water flow are used, then the bed behaves in a way described as collapse-pulsing. A high degree of bed circulation is created and higher grain velocities with consequent shear stress leads to rapid deposit detachment. Following air scour it is necessary to fluidise the bed with water in order to flush out deposits and trapped air.

The velocity data correlates well with the backwashing efficiency data, i.e. higher grain velocities result in better cleaning.

This thesis includes a video recording of selected representative experiments and copies of publications from this work.

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1 VHS Video tape (no sound) showing selected scenes from High Speed Video recordings of backwashing experiments. The description for this tape is in Appendix III.

1 INTRODUCTION

1.1 Rapid Gravity Filtration and Backwashing Practice

At water treatment works, rapid gravity, or deep bed, filtration is used to remove clay sized particles from the water as part of the overall treatment process. Dirty water flows through the deep, granular bed consisting of sand, alone, or in combination with other media, such as anthracite, granular activated carbon (GAC) or garnet. As the water flows through the bed by gravity the dirt particles (consisting of mineral and organic material) collect on the grains throughout the depth of the bed. The concentration of dirt deposits decreases with depth into the bed.

The accumulation of dirt deposits during filtration progressively reduces the permeability of the sand bed, creating a loss of water pressure so that an adequate flow rate can no longer be sustained. Additionally, there may be a breakthrough of deposits in the filtrate making it poorer quality. In water filtration this limit, due to clogging of the sand, is reached in about 24 hours, consequently daily cleaning of the filter sand is necessary.

Various cleaning techniques are used to remove deposits from the grains within the bed but all involve the upward flow of water which may cause full, or partial, fluidisation of the grains, either throughout or during the final stage of the wash, and deposits are washed out. Traditional American practice is to use auxiliary surface water jets compared with the British and European practice of using air scour in conjunction with water washing. Air scour is now taking over in North America but throughout the world it is employed in different ways: air scour may be with, or without, concurrent water flow, followed by a subsequent water wash; flow rates and durations vary and may not be used in the most efficient combination. All have the same objective: to dislodge and remove the deposits from the sand, with minimum energy and use of washwater, leaving the filter clean, ready for the next cycle of filtration. Ineffective backwashing leads to poor filter performance, and so a knowledge of backwashing mechanisms can lead to an improvement in the operating costs and efficiency of filter operation.

1.2 Factors affecting Backwashing efficiency

Filter cleaning efficiency is affected by how readily deposits are detached from the filter grains and by the ease with which these deposits can be flushed out from within the bed. The process uses clean water and so this usage must be minimised along with any equipment costs involved.

Factors affecting deposit detachment include:

* Properties of the filter grains; e.g. size, shape and surface texture - these affect the fluidisation behaviour of the bed as well as deposit adhesion;
* The adhesive nature of the deposits. This is affected by the natural constituents of the suspension and by any chemical pretreatment process;
* Detachment forces acting on the deposits, which may be due to grinding, grain collisions or fluid shear exerted by the flow.

Factors affecting the flushing out of deposits include:

* Upward water velocity; which must overcome the gravitational settling forces acting on the deposits;
* Porosity of the bed during backwash; loosened deposits must not become trapped within the bed.

Most research on the filter washing process has concentrated on the fluidisation behaviour of the granular bed, backwashed with water only. Very little research has been conducted into the actual detachment mechanisms involved, the use of air scour or the adhesive properties of the deposits and the forces required to detach them.

1.3 Problems associated with Poor Backwashing

The main operational problems associated with poor backwashing are as follows:

- if the surface mat of deposits is not broken up sufficiently then the formation of mudballs, which can be up to a few cms diameter, can occur. The use of surface water jets may encourage mudball formation;
- certain types of organic and mineral deposits may cause cementation of the filter grains if a build up results from repeated poor backwashing;
- expansion of the filter bed, as well as air flow rates, must be controlled to prevent loss of filter media in the backwash water;

- uneven distribution of backwash water within the filter bed may cause jets, boiling and dead patches (where grains experience inadequate cleaning);
- the final water wash rate must be sufficient for re-stratification of the bed in dual or multi media filters.

All of these problems result in poor filter performance leading to increased operational costs, due to more frequent washing requirements, or to a lower standard of filtrate, which may require additional treatment.

1.4 Development of the Experimental Technique

The use of optical fibre endoscopes (borescopes) coupled to a video camera in filtration research was developed at UCL (Fourie and Ives (1982)) and is useful for obtaining detailed visual information on processes occurring inside the filter bed. The use of conventional video equipment was extremely successful in observing filtration but was inadequate for the study of filter backwashing due to the rapid motion encountered. For this reason it was necessary to develop a system using a high frame rate so that the rapid motion could be "frozen" for analysis.

1.5 Objectives of this Research

The purpose of this research project was to establish what the mechanisms of cleaning are during filter backwashing. There were four aspects to the project as detailed below:

(1) Development of a laboratory scale experimental set-up and technique suitable for the study of filter backwashing mechanisms, by improving existing techniques employed at UCL.

(2) Simulation of filter runs using different suspensions and obtaining detailed visual information on behaviour inside the bed and on the efficiency of the backwashing process under varying conditions, using standard laboratory techniques.

(3) Development of software for communications and analysis of the video material, followed by detailed analysis of movement by means of velocity calculations.

(4) Comparison of results with existing models and recommendations for filter backwashing and design criteria.

2 BACKGROUND REVIEW AND BACKWASHING MODELS

Very little work has actually involved visual observation of the mechanisms occurring inside the filter bed during backwashing. Some relevant theoretical work examining the forces has been undertaken; additionally researchers in the field of chemical engineering have looked at theoretical and experimental aspects of fluidised beds (mainly gas). It has also been useful to consider work on the behaviour of granular materials, such as in soil mechanics. In this chapter work from various subject areas is reviewed and its application to this research is discussed.

2.1 Optical and Video Techniques

The use of optical fibre endoscopes in the study of water filtration has been described by Fourie and Ives (1982), Ives and Clough (1985), Clough and Ives (1986) and Ives (1986, 1987). The technique has evolved giving increasing image clarity until being used in conjunction with the high speed video equipment and described herein.

Fibre optic probes have been used in fluidisation studies as described by Peters *et al.* (1983) who used a borescope and high speed cine (210 frames per second) to observe particle ejection from surface bubbles in a fluidised bed. Saxena *et al.* (1987) used a borescope and black and white video camera recording at 30 frames per second to study solids distribution in a gas fluidised bed. From their photographs it appears that they had similar problems to those experienced at UCL in trying to eliminate the reflection of the light "ring" at the borescope tip. Joseph *et al.* (1986) used a motion analysis system incorporating a high speed video camera operating at up to 2000 fps to take external recordings of fluidised beds of glass spheres to look at patterns in particle behaviour. High speed ciné (4000 fps) was used by Govan *et al.* (1989) to examine particle motion in turbulent pipe flow and obtain particle velocity measurements.

None of these techniques would have been suitable for studying internal mechanisms occurring during filter backwashing.

2.2 Fluidisation and Particle Mechanics

The mechanics of solid particles in fluidised beds has been investigated in the field of chemical engineering which concentrates mainly on gas, rather than liquid fluidisation. However, some of the theoretical aspects can be related to the mechanisms occurring during filter backwashing.

Kono *et al.* (1986, 1987) have looked at the collision forces in gas fluidised beds. In liquid fluidised beds, as in filter backwashing, there are no actual grain collisions (described in section 2.3.1) but similar forces exist due to approaching grains, although the energy will be transferred to the rapidly thinning fluid film which will exert a hydrodynamic shear force on grain surfaces. They found that as the fluidising velocity increases so does the collision force, presumably as the grains acquire more energy.

Chemical engineering literature on three phase fluidised beds provides some useful background for dealing with the mechanics of air scour when used with a cocurrent water wash, as, for higher water and air rates, the bed may approach three phase fluidisation. When air scour is used alone then although there are three phases present the bed is not in a fluidised state. Kitano and Fan (1988) have used an optical fibre probe (non-image carrying) to measure solids holdup and investigate the near wake structure of gas bubbles in liquid-solid fluidised beds. Jin *et al.* (1986) and Yang (1986) have looked at the effect of liquid and gas velocities and particle size on the behaviour of the bed and have considered energy dissipation rate for different velocities for application to heat transfer which may be a useful concept for applying to the energy required to clean a clogged filter.

Lee and Al-Dabbagh (1978) described experiments looking at three phase flow. They used a bed of particles and kept the gas flow rate constant while slowly increasing the liquid flow rate. At certain liquid flow rates *jumping* behaviour was observed in the top few cm of the granular bed. As the liquid rate increased the lower limit of the jumping zone extended downwards. This caused consolidation of the bed to 92% of its original height. As the liquid rate approached fluidisation the bed began to expand and as the flow is gradually decreased again the bed passed through the jumping regime. Their data graphs show marked changes in pressure drop and porosity at around 40 - 50 % v_{mf}. This correlates well with the observations of Amirtharajah and co-workers described below.

Song and Fan (1986) stated that in three phase fluidised beds, the extent of turbulence, which is associated with the kinetic energy of the particles, is influenced predominantly by the gas flow rate. They have also observed that introducing low gas flow into a liquid-solid fluidised bed containing particles of less than 1.5 mm diameter induces bed contraction. This could be beneficial in filter backwashing as it may cause abrasion between grains, but as mentioned above air scour is not usually introduced into a fluidised bed as it would result in media losses.

Peterson *et al.* (1987) looked at bubble size and behaviour in three phase fluidised beds. They found that bed expansion was affected by the liquid flow rate only; the gas rate had no effect. Their explanation of the bed "contraction phenomenon is that these systems contain relatively large bubbles which have large wake volumes. The liquid present in the wake regions travels faster than the surrounding liquid, so that an increase in the number of bubbles would increase the amount of liquid in the wake region. Since this liquid, normally used to fluidise the solid particles, is diverted to the solids-deficient wake regions the solid bed actually contracts." Bed contraction was thought to be dependent on particle size and 3 mm appears to be the critical value above which contraction does not occur. The authors also pointed out that the Richarson-Zaki correlation does not hold for the transitional regime between a fixed and a fluidised bed and so developed a new model to cover all 3 regimes. From their experimental investigations they found that the minimum bubble size occurs near $v_w = v_{mf}$.

Various models can be found in the literature from soil mechanics. Many researchers have based their models on the kinetic theory of dense gases; e.g. Pasquarell *et al.* (1988) developed a model for obtaining the collisional stresses in granular flows, and, kinetic theory of gases was also used by Syamial (1987) in modelling fluidisation. These models often compared well with their experimental data. Haff and Werner (1987) have performed a computer simulation of collisions of inelastic spheres and have discovered that grain positions are not totally random and that the spheres have a tendency to form clusters of higher number density which has also been observed in fluidisation. Grains can get locked in these clusters for thousands of collisions. From the model, velocity distribution functions for the grains were obtained which were skewed. Other models have been proposed by Currier and Herman (1987) and Durst *et al.* (1984). Schulenberg and Müller (1987) have looked at two phase flow through beds of particles and have developed a 1-D model which takes into account interfacial drag forces between the liquid and the gas, although here the particles are fixed, it may provide some useful information on the behaviour of the gas-liquid interface when examining mechanisms during combined air and water backwash.

Liquefaction of sand has been simulated by Hakuno and Tarumi (1988) and some of the ideas in this model may be applicable to fluidisation of sand, although their model is based on spherical particles. Shen *et al.* (1988) have modelled collisional stresses in a dense fluid-solid mixture and have taken into account the drag effect of the fluid on the colliding particles and the consequent reduction in their energy. They have neglected interstitial fluid stress but their model has shown that the fluid drag force tends to infinity as particles approach each other. Again the model is based on idealised spherical particles which must behave differently from irregularly shaped sand grains. They point out that stresses in the mixture come from both the solid and fluid phase, although the fluid phase was neglected in their study.

Norman-Gregory and Selig (1988) have studied the volume change behaviour of vibrated dry sand and have identified resonant frequencies which give rise to maximum accelerations and greatest volume reduction. It is possible that collapse-pulsing (discussed below) is a condition of resonance in the sand bed, thereby causing contraction and high grain accelerations.

Tsotsas and Schlünder (1988) on considering axial dispersion in packed beds have looked at types of flow nonuniformity and have identified three types:
- microscopical, in the capillaries between grains,
- mesoscopical, due to areas of different grain packing, and
- macroscopical, due to wall effects.

These flow patterns may be observed during the filter backwashing process.

2.3 Filter Backwashing and Detachment Mechanisms

Most research on the filter washing process has concentrated on the fluidisation behaviour of the granular bed, backwashed with water only. This does not take into account the nature and behaviour of the deposits, only the properties of the grains and the behaviour of the water (velocity, viscosity). Only recently has work been devoted to the actual deposit detachment during the cleaning process.

2.3.1 Water Only Backwash

There has been much discussion about the forces causing deposit detachment during the backwashing process. For water wash, Amirtharajah (1978) concluded that particle collisions were rare in a fluidised sand bed and so the principal mechanism of cleaning is fluid shear. He developed a theory that predicts the maximum fluid shear at porosities between 0.65 and 0.70 (40 - 50 % expansion for graded sand) when there is maximum turbulence. The theoretical proof follows:

The mean velocity gradient for non-laminar conditions is given by

$G = (P/V\mu)^{1/2}$ where P/V is the power dissipated per unit volume of the fluid and μ is dynamic viscosity.

The power is derived from the pressure loss (resulting from drag) across a fluidised bed, which is a function of the expanded porosity ε_e. The relation between upflow superficial velocity v and expanded porosity is given by the Richardson-Zaki equation:

$v = v_s \varepsilon_e^n$ where v_s is the settling velocity of a single grain, and n is an empirical exponent representing the fluid flow regime, n=5 laminar, n=2.5 turbulent.

By combining these equations and differentiating, the maximum velocity gradient (and therefore the maximum shear stress) occurs when

$\varepsilon_e = (n-1)/n$, which for water washing of sand was $\varepsilon_e = 0.68$. This represents only the drag shear stress for a water fluidised bed.

This optimum bed expansion is constrained by the fact that particulate fluidisation is an inherently weak cleaning process because of limited collisions and abrasion between grains. Air scour and surface wash should promote grain collisions and so enhance the cleaning process.

Evidence in support of the fact that particle collisions are not significant during fluidisation includes: (i) the observation that during laboratory experiments there is no abrasion of experimental filter columns made from perspex, although the behaviour at the column wall differs from inside the bed and so this may be an indication, but not conclusive proof, of the lack of collisions, and (ii) in order to maintain the grains in a fluidised state there needs to be flow of a thin film of liquid around each grain. A third point has often been argued (e.g. Amirtharajah, 1978); if the grains actually collided then there would be an upwardly decreasing particle number density instead of the abrupt change that is observed at the top of the bed. This is not correct as the grains would behave in the same way even if no actual collisions took place since they still approach each other and rebound in a similar way. Whether this rebound is caused by actual grain to grain contact, or by the resistance of a thinning fluid film the effect is the same.

The behaviour of the bed is more likely to be governed by the effects of fluid drag, gravity and surface tension. In fact it is quite likely that there is a slight upward decrease in particle concentration resulting from stratification of the graded sand; the finer fractions will experience greater expansion than the coarser fractions for a given upflow.

Point (i) above has been noted independently by Joseph *et al.* (1986) who observed a *lubrication layer* of clear water at the walls of fluidised beds.

Expansion of filter media has been investigated by many researchers, e.g. Moll (1986). Initially, Cleasby and Fan (1981) tried to take into account the irregular shape of filter media grains when predicting minimum fluidisation velocity (v_{mf}) and expansion of the media by using both sphericity and dynamic shape factor. They suggested that d_{90} should be used in calculations of v_{mf} and a 30% safety factor added to ensure that the larger grains will be agitated. Later, Dharmarajah and Cleasby (1986) discussed models and tried to evaluate the effect of particle non-sphericity and came up with an equation to predict the velocity-voidage relationship of particulately fluidised systems. Similar work has been done by Sholji (1987) and Sholji and Johnson (1987) who consider the dynamic shape coefficient which varies with grain size, presumably due to a relationship between surface area and volume; experiments were performed with unisize media which are not representative of most filter sands. Muslu (1987) developed a fluidisation model based on spherical particles which is able to take into account the angularity of grains when predicting bed expansion; an equation for v_{mf} was obtained which is a function of grain sphericity, density and bed porosity but this would not allow for the size range often encountered in filter media. Quaye (1987) has developed a model predicting the expansion and optimum backwash rates of multi-layer filters which has been experimentally verified using different media.

The behaviour of dual media filters when backwashed with water has been investigated by Ben Aïm and Ventresque (1986). Activated carbon or anthracite were used with sand and measurements were made of media loss and expansion and the velocity gradient predicted from theory for different wash rates. The results are in agreement with other researchers', but they note the importance of washwater temperature in affecting bed behaviour, which is due to the variation in water viscosity.

Surface jets were recommended by Mackay (1988). He also suggested that backwash water valves are opened slowly (over a time period of 30 - 45 s) to prevent loss of media, particularly if there are pockets of gas in the bed. Beds should be backwashed every 48 to 72 hours, depending on the influent water quality, and surface jets aid cleaning of the top layer of the filter which does most of the filtering and therefore gets dirtiest. If surface jets cannot be used a 2-stage method of backwash is recommended; a low rate wash (~20 m/h for 3 - 5 min) then a high rate wash. The low rate wash is thought to cause grain collisions and scrubbing while the subsequent high rate wash expands the bed by 20 - 30 % and flushes out the deposits. The actual backwash rates should be determined by taking into account media size, water temperature, etc..

Huang and Basagoiti (1989) developed a model to predict solids dislodgment during the filter backwashing operation. The use of the parameter, K, to characterise the adhesive properties of different suspensions is a useful innovation and their experimental data makes a valuable contribution to the subject. However, the model is developed based on two assumptions which will be discussed in Chapter 7.

Backwash time and turbidity of washwater has been investigated by Bhargava and Ojha (1989) who did experiments with spheres made from flour, which they argued had good adhesive properties. Unfortunately, the writer believes that these properties are possibly very different from those of conventional filter media and some verification of the properties would be required. The spheres were then coated uniformly with clay and agitated, in a manner which simulated backwashing and the decrease in sphere diameter was noted. From this a mathematical model was developed based on the assumption that the rate of decrease in sphere diameter is proportional to the deposit remaining. The model has then been applied to a filter assuming different volumes of deposit in the different "layers" of the filter and the variation of backwash turbidity with time has been predicted, by adding the contributions from the different layers. This is a useful concept for modelling backwash but more experimental verification of the model is required and no account is taken of different backwashing methods which will result in different turbidity-time variations. The authors have data on the porosity of a bed after filtration at Dehradun water works; this data indicates very little reduction in porosity (~2%) which would seem untypical of most filters prior to washing, and certainly does not match the data used for their model so the comparison is not valid.

Ahmad and Chaudhuri (1989) have described backwash water quality at the Kanpur treatment works in India where the two sets of filters use different backwash procedures; water only and air followed by water wash. They have made turbidity comparisons for single and dual media filters as well as for the two different backwash procedures. Unfortunately, filtration rate varied and media sizes were not given so it is difficult to obtain any useful information from the data.

Some of the problems encountered at treatment works, which may result from poor backwashing practice, are described below.

During pilot plant studies for Manganese removal in Brazil, Bratby (1988) noted that filter grains became black, due to manganese coating, after 2 or 3 filter runs, and after several runs an increase in bed height (~5%) was noticed. This proved that the water only backwash employed was not sufficient to clean off these adhesive deposits which would eventually form mudballs. This could be due to the fact that a maximum of 13% expansion was achievable, which falls short of Amirtharajah's (1978) optimum of 40 - 50 % expansion for graded sands.

Similar problems have been experienced in Bedfordshire, U.K. where raw water containing iron and manganese (Clark, 1988) has led to increases in filter grain size and consequent filter inefficiency along with mudball formation. He noted that iron-bearing water can be treated by water softening, but this causes accumulation of chalk deposits on the filters to the extent that agglomerates of grains were formed that required a pneumatic drill to break them up. The use of air scour in some filters did not prevent the build-up of deposits.

2.3.2 Introduction of Air Scour

To improve cleaning efficiency, it is important to use techniques that increase the shear forces acting on the grains either by promoting grain collisions or by increasing fluid shear forces, assuming fluid shear on its own is insufficient for detaching the more adhesive deposits. It is generally acknowledged that air scour and surface wash should have this effect and so enhance the cleaning process. Surface wash, however, is restricted to the top few cm of bed and so will have little effect on deeper deposits that result from deep bed filtration.

This research has been taken a stage further by considering the action of air scour in dislodging deposits from grains prior to their being flushed away by the upflowing water. It was noted that the passage of air bubbles through the sand bed causes rapid movement of the grains as the bubbles pass. The sand grains and adhering deposits collapse in the wake behind a bubble at high velocity. The behaviour of the bed varies for different combinations of air and water flow rates.

Prior to identifying collapse-pulsing, Amirtharajah *et al.* (1981) had begun by looking at the mechanics of air scour. The work of Cleasby (1977) was discussed, who thought it unnecessary to fluidise the bed after air scour when a single filter media is used. It is likely that this would cause problems with air trapping within the bed. Secondly they noted that there is a potential problem with air scour disturbing the gravel supporting the filter media but it is effective in eliminating mud ball formation (except see Clark, 1988, above), and the British practice of low water rate after air scour does not flush out all of the loosened deposits (and presumably the trapped air). All the evidence, however, indicated that air scour was an effective cleaning method.

Simmonds (1963) criticised the British system as air used alone forces out the water and makes grains less mobile as well as having a tendency to form channels. He proposed using cocurrent water flow sufficient to expand the bed by ~10cm; this is a higher flow rate than that required for collapse-pulsing.

Amirtharajah *et al.* (1981) looked at bubble mechanics in liquids and fluidised beds. Bubbles in the fluidised bed behave as in a liquid. Experiments investigated bubble behaviour in still and upflowing water and in sand. The behaviour of different air diffusers was compared. Cine film was used to obtain information on bubble size, shape, velocity and rise behaviour. Larger bubbles had higher velocities which decreased mid depth due to shedding of smaller bubbles in the wake. Upflowing water had no effect on bubble behaviour. For the three phase investigations it was noted that bubbles were larger and their velocities lower on leaving the sand bed when there is a sub-fluidising water flow, giving a reduction in media loss. They suggested that the combination of large bubbles and lower velocity may be the reason for improved cleaning, as there appeared to be continuous movement of the bed.

Amirtharajah and Trusler (1982) examined loss of filter media during air scour both with and without sub-fluidised water flow. They found that for air alone there was a linear increase in media loss with increasing air flow rate. For combined air and water flow, again the relationship was linear but there was a change of slope corresponding to the change from channel to bubble formation within the bed (i.e. the onset of collapse - pulsing). Additionally, there was a lower media loss when combined air and water are used except for water rates of ≥70% v_{mf}. They suggested that the change in slope at collapse - pulsing (which occurs at around 40% of v_{mf}) is due to the improved energy transfer from the air to the grains. To minimise media loss a weir height of 75 cm is recommended (but it is dependent on the media used) and a wash sequence as follows:

1. Drain filter so that water is level with top of media

2. Start sub-fluidised water flow
3. When water is 7 - 15 cm above bed slowly start air flow
4. Stop air scour when water level is 15 cm below weir lip
5. Wash with water at 20% expansion

Pilot scale experiments, described by Regan and Amirtharajah (1984), have been performed to investigate whether collapse-pulsing optimises particle detachment during backwashing. Three phase bed behaviour in the unfluidised state, the collapse-pulsing theory (Amirtharajah, 1984) and experimental results are discussed in this paper. The observations on bed behaviour agree with those of Hewitt and Amirtharajah (1984) and can be summarised as follows:

Air plus zero water flow - smaller air bubbles travel up the pores. Near the surface, effective stresses between grains are reduced, resulting in enlarged channels of air and the development of turbulence as the air leaves the bed. Since the bubbles in the bed are small they have little effect on cleaning as there is minimal grain movement, except at the surface. No risk of media loss.

Air plus low water flow rates - there is an increase in pore water pressure and so a decrease in effective stresses and channels of air form deeper in the bed. The authors suggested that there is less abrasion between grains when channels form due to the persistence of preferential air channels rather than random air movement.

Air plus water flow rates causing collapse-pulsing - air cavities form, expand and then collapse as air escapes from the top of the cavity, where there is zero water flow (a stagnant zone), and forms a new cavity. This cycle repeats throughout the depth of the bed. As the air cavities collapse, there is active Rankine failure of the grains in the wake of the bubble. During collapse-pulsing there is maximum grain abrasion and relative movement so theoretically this should give best cleaning. Collapse-pulsing developed at the bottom of the bed and spread upwards.

Air plus water rates approaching v_{mf} - effective stresses are reduced so that the bed behaves like a liquid. Bubbles move upwards with the liquid and behave as observed in a liquid. The writer believes that this may be three phase fluidisation. Maximum media loss occurred.

Regan and Amirtharajah (1984) used glass beads for the filter media and known amounts of alum sol suspensions during filtration. Backwash water was collected and analysed for particle numbers. The peak in particle detachment corresponded to water flow rates giving collapse-pulsing for a series of different air flow rates tested. This data also showed a second peak at ~80% v_{mf}, preceded by a trough, which could be a feature of the experimental set-up or may be genuine. From the experiments they deduced that for $v_w < v_{mf}$ grain collisions promote particle detachment and for $v_w > v_{mf}$ removal is the result of hydrodynamic shear forces. They suggested that these two mechanisms are entirely separate but it is more likely that their relative importance changes. Additionally, evidence suggests that with real filter media the onset of fluidisation is more gradual due to the media size range. The experimental results were compared with theory and another version of the collapse-pulsing equation was obtained by linear regression which compares well with the theoretical version obtained by Amirtharajah (1984) being of the form

$$\%(v/v_{mf}) + const.Q_a^2 = const.$$

but the equation does not hold for $Q_a < 4$ ft^3/ft^2 per min. (73 m/h).

It is possible that the real situation where the particles are non-spherical and the suspension filtered contains particles of differing sizes and adhesive properties would give rise to different patterns of efficiency from those described above but the experimental data provides a useful background to more detailed investigation.

Hewitt and Amirtharajah (1984) concluded that the efficiency of backwashing with air scour is related to grain abrasion. Intensity of abrasion is related to: (i) effective stresses between grains, and (ii) the magnitude of their relative movement. The two effects are contradictory with increasing water flow, which indicates the existence of an optimum. It was confirmed that media losses were kept to a minimum during collapse-pulsing and that it caused mixing within the bed. Mixing was also noted for dual media filters when air scour is used alone (Bablon *et al.*, 1988).

Following all of this experimental work, Amirtharajah (1984) was able to obtain the collapse-pulsing equation by combining concepts from soil mechanics and porous media hydraulics. The air pressure within a bubble is equated to the stresses between grains in an active Rankine state plus the pore water pressure. The resulting equation for air rates (Q_a) in m/h is:

$$0.0013Q_a^2 + \%\frac{v}{v_{mf}} = 41.9.$$

After the work of Amirtharajah and co-workers identifying collapse-pulsing, Roberts (1986) examined the use of combined air and water flow in filter washing, particularly in relation to bed behaviour. He has not looked at the effect on a clogged bed or the cleaning efficiency. Existing theory and observations on three phase flow from the field of chemical engineering have been related to the Amirtharajah (1984) and Hewitt and Amirtharajah (1984) observations described above. Experiments were performed to find an improvement on the empirical relationship between the water velocity (v_l) and the gas velocity (v_g) for collapse-pulsing conditions. He described how when there is combined air and water flow through the bed at water flow rates below v_{mf} the water transmits the energy from the air to the grains. When the bed is washed with fluidising water only there is stratification of the media, whereas with simultaneous low water and gas flow mixing occurs, which is in agreement with Amirtharajah (1984). Although this mixing may be desirable, he does not mention that it is necessary to fluidise the bed after air scour to flush out loosened deposits and trapped air which will then re-stratify the bed. All the work reviewed by Roberts suggests a correlation of the form

$$v_l = b - a v_g$$

and for $v_l < v_{mf}$ there is *jumping* activity within the bed. This equation has a similar form to that of Hewitt and Amirtharajah (1984).

Roberts' results agree with those of Hewitt and Amirtharajah (1984) which suggested that a lower water rate is required if higher gas rates are used. But he suggested that their linear relationship between v_l and v_g is a very crude approximation as the data lies on a definite curve. The fact that high gas rates reduce the amount of water required could result in cost reduction at the treatment works. The writer suggests that consideration must also be made of the amount of water required to flush out the trapped air as well as the cost of providing high rate air scour.

Roberts has observed from experiments:

(1) bed contraction at collapse-pulsing;

(2) collapse-pulsing starts at the base of the bed and works upwards as water rate increases (agrees with Hewitt and Amirtharajah (1984));

(3) particles are lifted from the bed as bubbles emerge from the surface;

(4) good bed circulation at collapse-pulsing allowing all grains and deposits to pass through regions of maximum turbulence.

He suggested that the correlation may be of the form

$$v_l \propto \frac{d^{2/3}}{v_g^m} \quad \text{where} \quad \tfrac{2}{5} < m < \tfrac{1}{2}.$$

The use of combined air and water backwash in wastewater filters has also been studied by Addicks (1989). Various different filter media were used to examine bed behaviour; these included glass beads, expanded clay spheres and coarse silica sand all of size greater than d = 2 mm. He pointed out that evidence suggests that water only cleaning is insufficient to remove the active biofilm from the surface of the grains and that air scour should enhance cleaning and eliminate the need for chemicals. Using an experimental filter column he looked at expansion/contraction of the bed, grain movement and the scouring action produced by air plus water and tried to explain the observations and predict optimum backwash. Layers of coloured beads were put in the bed to observe mixing and movement and starch coated glass beads were used to evaluate scouring efficiency.

Addicks found that the coloured beads moved more above the air supply nozzles, indicating good mixing, and that maximum movement was for water rates < 60 - 70 % v_{mf}. This differs slightly from Amirtharajah and co-workers' observations of collapse-pulsing where maximum (i.e. complete) mixing takes place at ~ 40 % v_{mf}. It is possible that a higher water rate is required to achieve collapse-pulsing in this larger grained system. Maximum bed contraction of 5 - 10 % occurred at ~ 60 % v_{mf} which corresponded to the maximum removal efficiency for water rates lying between 40 % and 70 % v_{mf}, which covers collapse-pulsing. A depth variation in cleaning was observed which would support the observations of Amirtharajah and co-workers that the onset of collapse-pulsing occurs at different flow rates for different depths. This is due to the effective stresses within the bed and the variation in media size. He said that in the transition zone from the packed to the three phase fully fluidised bed (at ~ 60 %v_{mf}) the scouring action is greater than that in a bed fluidised with water only.

Addicks' experiments suggested that most of the glass beads lose their coating in the first 1 - 2 min of air and water wash and therefore a repetitive cycle would be more efficient than a single prolonged wash. This implies that it is the initial change in the bed that causes the cleaning rather than the motion due to combined air and water flow, otherwise a prolonged wash would be as efficient. In fact, Addicks assumed that it was the movement during bed contraction that was the main cleaning aid, rather than the collapse of the bed in the bubble wake as described by Amirtharajah (1984). All the data indicated a maximum efficiency around 60 % v_{mf}, which may correspond to collapse pulsing for larger media. Amirtharajah's theory implies that % v_{mf} cannot exceed 42 otherwise the v_g^2 would be negative so either the theory does not hold for larger media or

Addicks' findings disagree. Although the work of Regan and Amirtharajah (1984) suggested that the % v_{mf} required to achieve collapse-pulsing gets lower with increasing media size.

Bed contraction is explained by the wake reducing the quantity of water required to fluidise the bed. The latter may be so due to the higher water velocities flowing past bubbles but it is not clear how this would cause contraction. The writer believes it is more likely that contraction is due to a rearrangement in grain packing as a result of agitation from passing air bubbles. Four methods for predicting the onset of three phase fluidisation were considered and he concluded that the equation derived by Amirtharajah (1984) comes up with a value that is too low for v_w. This is probably due to the fact that the equation describes the onset of collapse-pulsing and not three-phase fluidisation (although the two may correspond).

Addicks later (1990) discussed the problems of calculating the three phase minimum fluidisation velocity (v_{mf3}) due to problems in particle size characterization and the fact that deposits on the filter grains affect v_{mf} and v_{mf3} due to the resulting size change.

2.4 Possible Mechanisms of Detachment

Possible mechanisms of detachment of deposits from the grains include fluid shear, grain collisions and grain abrasion.

There is little doubt about the presence of shear forces at the sand grain surfaces; they account for all, or most, of the drag forces opposing settling of the grains during fluidisation. Also, in the apparently violent movements of the grains during washing, two grains approaching one another have to displace the water between them. The thinning water film flows radially from the diminishing separation creating a high laminar shear stress. Furthermore the passage of an air bubble can create a thin water film between the bubble boundary and the grain surface. This again creates a high laminar shear stress (Ives and Fitzpatrick, 1989).

Consequently, the resistance of deposits, and deposit attachments, to shear stress seems to be a fundamental property governing the detachment process. This will be affected by the nature and properties of the deposits.

In the late 1960s the *turbulent bursts* concept emerged where they periodically and locally penetrate the laminar sublayer and provide a force to loosen particles. The concept of random turbulent bursts with given spatial and temporal frequency ties in with experimental reality and allows for derivation of re-entrainment rates, but does not explain the exact interaction between the fluid and the particles. It was expected that detachment rates would be strongly dependent on the frequency of bursts and hence on the Reynolds' No., R_e.

The action of turbulent bursts in deposit removal was considered by Amirtharajah and Giourgas (1981). The authors modelled particles detaching from a grain as a result of lift forces from the turbulent burst, which overcome the particles' adhesive forces. Ultimately they achieved equations for the mass transfer rate. Calculations which used average interstitial velocities to obtain removal indicated that fluid shear forces would always leave a layer ~ few nm thick on the sand grain. The writer believes that it would have been better to use the maximum interstitial velocity for these calculations as this would determine maximum detachment. They have considered the relative effectiveness of the drag and lift forces but have not considered the rolling movement resulting from uneven forces at the outer and inner edge of the particle, as described by Silvester and Sleigh (1985). They have concluded that the drag force, which is larger, could initiate movement and then the particle is carried away by the lift force from a turbulent burst. From the model it was concluded that "total removal of the dirt particles is impossible by fluidisation during backwashing" as the lift force due to turbulent bursts cannot overcome Van der Waals forces very close to the grain; the writer believes that the model neglects too many factors, e.g. varying nature of deposits, to draw this conclusion satisfactorily. Evidence was quoted on growth of filter grains over periods of years, with almost a 50% increase in grain diameter. The nature of this growth, i.e. chemical precipitation or biological, was not stated but it was thought to result from lack of abrasion between grains during backwashing leading to a gradual build-up. In this case more abrasion between grains is required, such as that provided by air scour.

Braaten *et al.* (1988) have looked at turbulence and particle detachment in boundary layer flows and noted that movement of particles from positions on the surface may occur in several ways. The least complex is detachment by fluid forces, called non-saltating particle resuspension, which occurs when fluid forces penetrate the boundary layer to the layer of particles and exert sufficient drag and lift forces to overcome adhesion. The mechanism allowing fluid forces to penetrate to the particles is hypothesised to be related to energetic coherent intermittent structures which disturb the viscous sublayer surrounding particles, permitting fluid forces to overcome particle adhesion, i.e. turbulent bursts.

Wen and Kasper (1989) suggested re-entrainment of particles is the result of competition between adhesion and fluid dynamic lift forces acting on an ensemble of particles over time. In the 1960s the adhesion force was seen as balanced by a steady fluid drag force exerted on the particle within the laminar sublayer which somehow caused the particle's upward motion. Entrainment occurred the instant the fluid force exceeded adhesion (a threshold value). This model cannot predict the kinetics of the process because a steady state fluid force does not contain a time element. This is acceptable for liquids as all particles seem to come off when fluid flow exceeds a certain velocity. Wen and Kasper (1989) also reviewed work that considered the particle to be elastically bound in a potential well, oscillating around a mean energy supplied by the r.m.s. fluid lift forces. The particle accumulates energy from successive bursts until it is released. Consequently particles may detach even when individual bursts are not strong enough. It was also suggested that the initial burst of deposit detachment (up to 90 % in 10 ms was observed) may be caused by the shockwave generated when flow is turned on, the rest detached at a rate α 1/t. This shockwave may be responsible for a lot of detachment in filter backwashing.

Silvester and Sleigh (1985) have looked at the effect of shearing boundary layer flow caused by surfaces on which micro-organisms may be attached. When the thickness of the boundary layer exceeds a critical value then turbulence develops which causes a dramatic rise in the mean shear stress but additionally the individual shear stress maxima will be even higher. The authors state that "an organism attached to a substratum covered by a boundary layer is in a shear flow, with the outer parts of the organism subject to higher velocities than parts near the point of attachment". The same will apply to deposits on filter grains and this will give rise to the deposit experiencing a torque, in addition to the viscous drag force pulling it away. These coupling forces may cause the organism, or deposit, to roll along the substratum. The magnitude of the coupling force increases with r^3, so bigger deposits will experience greater torque which has to overcome the particle's adhesive forces. The authors have quoted shear stress values in the range 3 - 33 $N.m^{-2}$ required to remove bacteria from a glass surface, but they note a large variation in adhesive behaviour (which may be related to contact area) of single celled organisms, which would affect filter backwashing. They also note then when flow is turbulent then the maximum forces are responsible for detachment of microorganisms. The writer believes that the same applies to deposits in backwashing and the scale of turbulence and the range of velocities will control deposit detachment.

The researchers listed above have considered the detachment mechanisms related to fluid shear. In filter backwashing grain collisions and abrasion also cause detachment. In the fluidised bed grains approach extremely closely, but may not collide, which causes greater fluid shear stresses. It is unlikely that turbulent bursts would occur even in the fluidised bed even when there is maximum turbulence at 40 - 50 % expansion. The fluidised bed is in the transitional regime between laminar and turbulent behaviour, i.e. the Reynolds number is not high enough and the boundary layer is too thick for the development of turbulent bursts which casts doubt on the validity of the model of Amirtharajah and Giourgas (1981) described above. The role of grain abrasion in deposit detachment has been discussed in the preceding section.

2.5 Summary

The review of the literature reveals that very little is known about the mechanisms of deposit detachment during filter backwashing and the way the bed behaves under different conditions.

Development of the endoscope and video technique was needed in order to obtain a detailed understanding of bed behaviour during backwashing. None of the existing techniques could provide adequate frame rate in conjunction with high level illumination in order to freeze rapid motion.

Examination of theory and experimental evidence in the fields of fluidisation and particle mechanics have revealed that the behaviour of a fluidised bed is very complex and it is not clear whether particles actually collide, or whether they just approach each other extremely closely. There is no theoretical or experimental proof of whether collisions actually occur. When the bed is not fluidised, or when it is undergoing combined air and water wash, then the particles are in contact with each other most of the time which may result in abrasion. However, the literature provides evidence for (i) the fact that particle collisions are insignificant in a fluidised bed, and (ii) the reinforcement of Amirtharajah's (1984) observations on the collapse-pulsing phenomenon under combined air and water flow.

Work on deposit detachment mechanisms explores turbulent bursts which penetrate the boundary layer. These would not occur for the subfluidised backwash rates as flow is laminar but for higher wash rates, giving 40 - 50 % expansion, maximum turbulence does occur as stated by Amirtharajah (1978). Since the majority of deposits are detached prior to bed expansion then it is unlikely that this is a major detachment mechanism. The major detachment mechanism is due to fluid shear forces.

Abrasion between grains is thought to give most effective cleaning, and air scour, particularly in conjunction with water at collapse-pulsing rates, is thought to maximise abrasion.

3.1 Filter System

A model filter apparatus consisting of a 0.115m internal diameter, 1m high clear perspex column has been used for the experiments (Fig. 3.1). It was designed for the previous research project which used fibre optics in water filtration studies (Clough and Ives, 1986). At varying heights on the column are tapping points for manometers, sampling and visual observation by borescope insertion (described below in section 3.2). Suspensions are mixed in a 114 litre tank by a pump also supplying the constant head tank which then supplies the filter by gravity. The filtered water emerges at the base of the column at a rate measured by a flowmeter (range of 0.2 - 1.5 l/min).

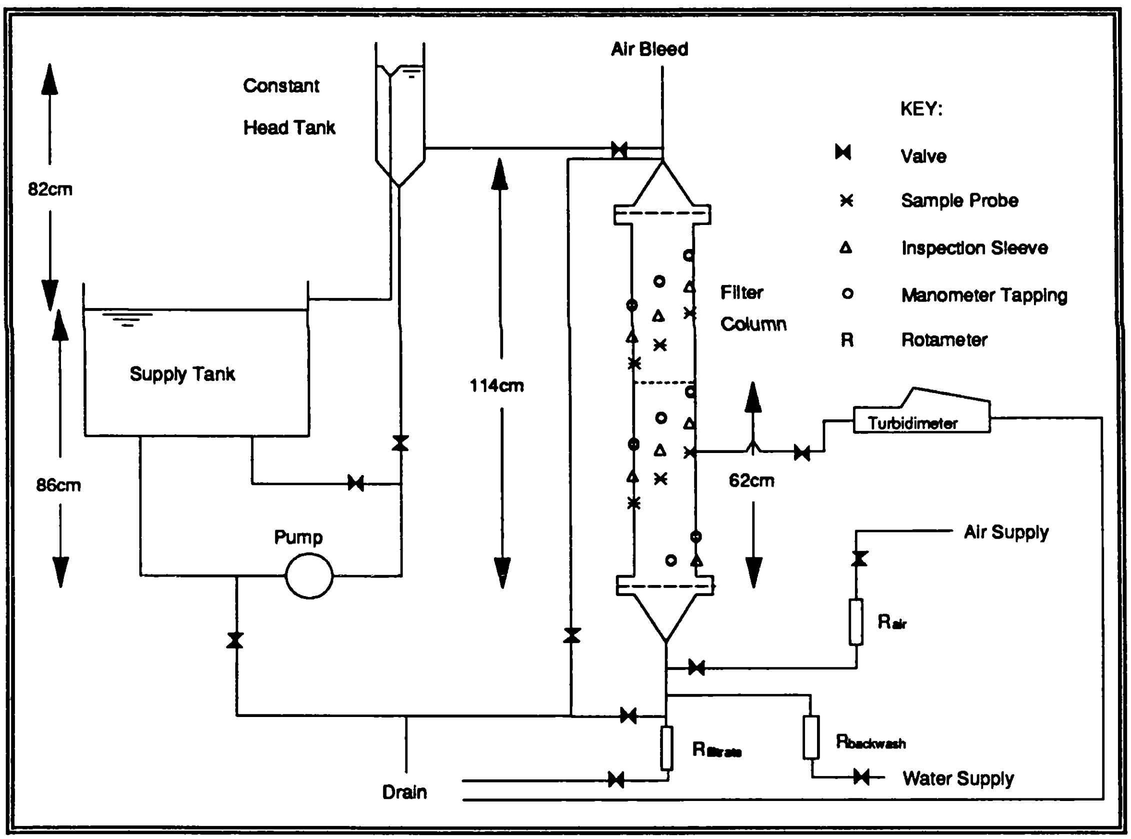


Fig. 3.1. Diagram of filter apparatus.

Modifications were made to the existing filter column for the purpose of the backwashing research as follows:

(i) A compressed air supply was connected to the base of the filter column via a flowmeter

(ii) The borescope insertion sleeves were enlarged to accommodate the larger diameter borescope necessary for high speed video recordings

(iii) Various valves and flowmeters were added to aid the experimental procedure.

For backwashing and air scour, water and air enter at rates measured by flowmeters at the base of the column and flow upwards. The air flowmeter has a range of 2 - 25 l/min and the backwash water is measured by two flowmeters in parallel which can be switched depending on whether a low or high flow rate is used. These flowmeters have ranges of 1 - 10 l/min and 2 - 22 l/min, respectively.

The filter media can be changed or the bed depth adjusted by dismantling the column. The depth of media could be varied up to a maximum of about 0.85m, above which losses would occur during the backwashing process, due to the bed expansion. The media is supported by a brass mesh under which are glass spheres (~1.5 cm diameter). This underdrain arrangement is designed to create a uniform flow pattern through the sand bed during filtration and backwash.

3.2 Turbidimeter

A Hach continuous flow Ratio/XR Turbidimeter, capable of measuring up to 2000 NTU, was used to measure, and record on chart, the turbidity of the backwash water. It was connected either to the washwater outlet pipe, or, to one of the sample ports for measurement of the turbidity of the emerging wash water or within the bed, respectively.

3.3 Optical Fibre System

A rigid optical fibre endoscope (borescope) is used for internal examination of the filter bed away from the walls of the model filter column. An 8mm borescope (fig. 3.2 a) views the sand bed, in the direction of its axis, through a plane crown glass (BK-7) window set in a brass sleeve of 11mm O.D.. This sleeve arrangement provides the necessary minimum focussing distance (~4 mm) between the object (the grains) and borescope.

A series of 11 brass sleeves are inserted at different depths within the sand bed to allow for observation of depth variations in bed behaviour. Their bed penetration distance is adjustable for observation of any radial changes. Some of the glass windows have a graticule, consisting of two perpendicular pairs of 1mm separation parallel lines (25μm thick chromium), etched on the face in contact with the sand grains (fig. 3.2 b) . This graticule provides a means of calibrating the optical system. For sand of size d_{10}=0.56mm the borescope provides an area of view of approximately ten grains.

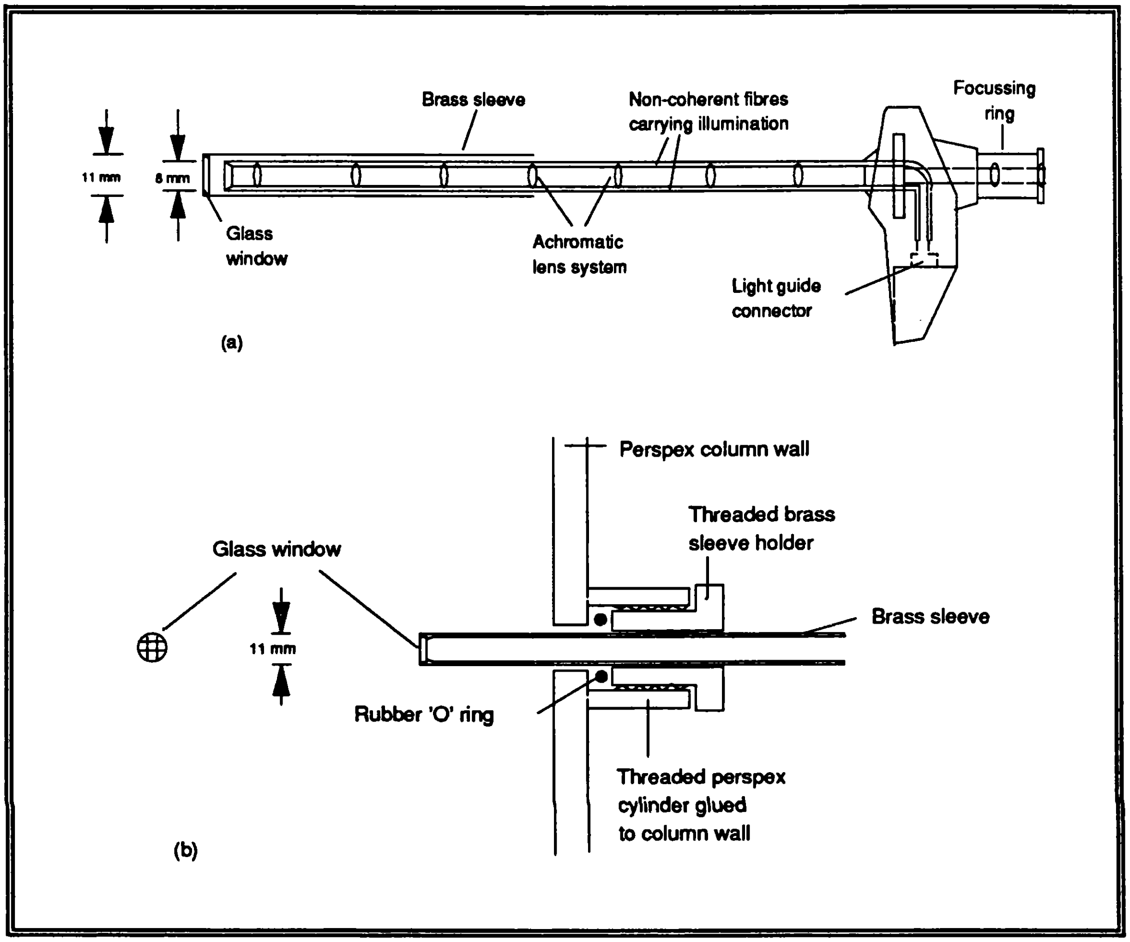


Fig. 3.2. Schematic cross section through (a) borescope and sleeve, and (b) borescope insertion port on wall of column.

The existing 150W light source was inadequate for high speed video recording so a 250W light source (fig. 3.3) was used. Initially this was provided by a 250W mercury arc lamp but was later replaced by a source using a 250W metal halide lamp. Light from the lamp passes along a flexible, liquid light guide to the borescope where the light is transmitted to the borescope tip via an annular bundle of fibres which surround the image carrying core. The illuminated region of the filter bed is viewed through the eyepiece of the borescope which has adjustable focussing. The image from the borescope tip passes through a series of lenses to the eyepiece which could be viewed with the naked eye, a still camera or a video camera.

Fig. 3.3. 250 W light source, liquid light guide and borescope.

3.4 High Speed Video System

3.4.1 Evaluation

The requirements of a video system to be used in this investigation were:

(i) the ability to provide a bright, sharp image of the sand bed when viewed through a borescope during backwashing;

(ii) slow motion and freeze-frame playback facilities for qualitative and quantitative analysis of the video images.

Two alternative high speed video systems were evaluated. The Kodak EktaPro 1000 provided monochrome images at rates up to 1000 pics/s full frame and 6000 pics/s for 1/6 frame. This system was not sensitive to the low light levels encountered when viewing through the borescope and so did not provide a bright enough image for analysis. The NAC HSV400 system provided 200 pics/s at full frame recording and 400 pics/s for half frame recording. Due to the lower frame rate this system was able to provide a bright full colour image using the borescope. Consequently a NAC system was purchased.

3.4.2 Description of the NAC HSV400 High speed video system

The high speed colour video camera provides a high resolution image. It is a high sensitivity, three tube colour camera with a built-in high speed shutter giving very short exposure times to freeze rapid motion. The shutter has four speeds giving 1/1000, 1/2500, 1/5000 and 1/10000 of a second exposure times. There are 0, 6 and 12 dB gain settings on the camera for increasing image intensity when light levels are low. Unfortunately, this also boosts the noise level resulting in a poorer quality image, due to the lower signal to noise ratio.

Each frame on the recorded video tape displays scene code and time information which can be used in subsequent analysis. The high speed video recorder uses standard VHS cassettes; the recordings are to the NTSC standard but the video output is to PAL standard, therefore PAL monitors are used and video material can be downloaded by connecting to a PAL video recorder. Recordings can be played back in various modes including normal playback, at 0.3 times the recording speed, slow motion, still playback (freeze frame), and search and jog (single frame advance) playback in both forward and reverse directions. The search playback mode provides frame rates between 2 and 1,200 pics/s for 400 pics/s recordings and between 1 and 600 pics/s for 200 pics/sec recordings. For high playback speeds, at the recording rate and above, noise bars appear in the image.

3.4.3 Experimental implementation of the NAC HSV400

For use with the borescope, a standard 50mm SLR camera lens is attached to the video camera which is mounted on a tripod with the lens having a standoff of around 1cm from the borescope eyepiece. The 50mm lens maximises light levels while at the same time providing suitable magnification. This standoff arrangement allows the camera to be moved to view different locations within the sand bed without mechanical interference or vibration of the bed itself, which is a problem if the borescope lens coupling device is used. The experimental set-up can be seen in fig. 3.4.

Magnification obtained by the combined borescope and video system is of the order of 100 times on the video monitor. This could be increased by using a larger monitor or a 3 times convertor, or similar, attached to the lens, if necessary. A disadvantage of the converter is the reduction in light levels making it unsuitable for use with the high speed video.

3.4.4 Video tape indexing system

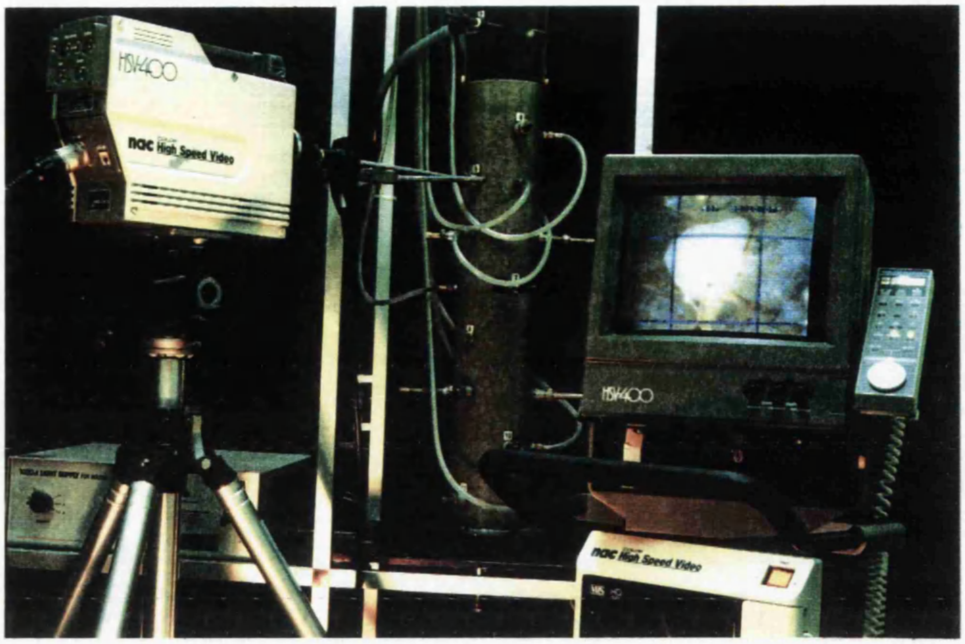
Tapes used for recording filter backwashing on the HSV are labelled from B1 to B20. Each tape contains recordings from a series of experiments and the separate experiments can be identified from the scene code, e.g. scene code 191 represents the first experiment on tape 19, 192 the second, etc. This number corresponds to the experiment number used throughout this thesis.

3.5 XY Coordinator and Computer Hardware

The NAC XY Coordinator V-78-E (fig. 3.5) complements the HSV equipment for video image analysis. It consists of a digitising tablet with a pen to move a cursor, displayed on the HSV400 screen with its X and Y coordinates, and a box of hardware for communicating between the HSV and a computer. Two communications interfaces are available; GP-IB and RS232C. The RS232C interface was used to provide the link with the communications port of a PC-AT IBM compatible machine; the DSC Turbo PC-AT.

The XY coordinator outputs x and y screen coordinates, scene code and time information, and various status messages via the RS232C line. The video output channel displays the cursor, coordinates and a dashed line, when used in trace mode, on the HSV400 monitor via a video mixer. The XY Coordinator has a set up menu where it is possible to select communications parameters, e.g. baud rate, which is the speed at which signals are transmitted or received by a device.

(a)



(b)

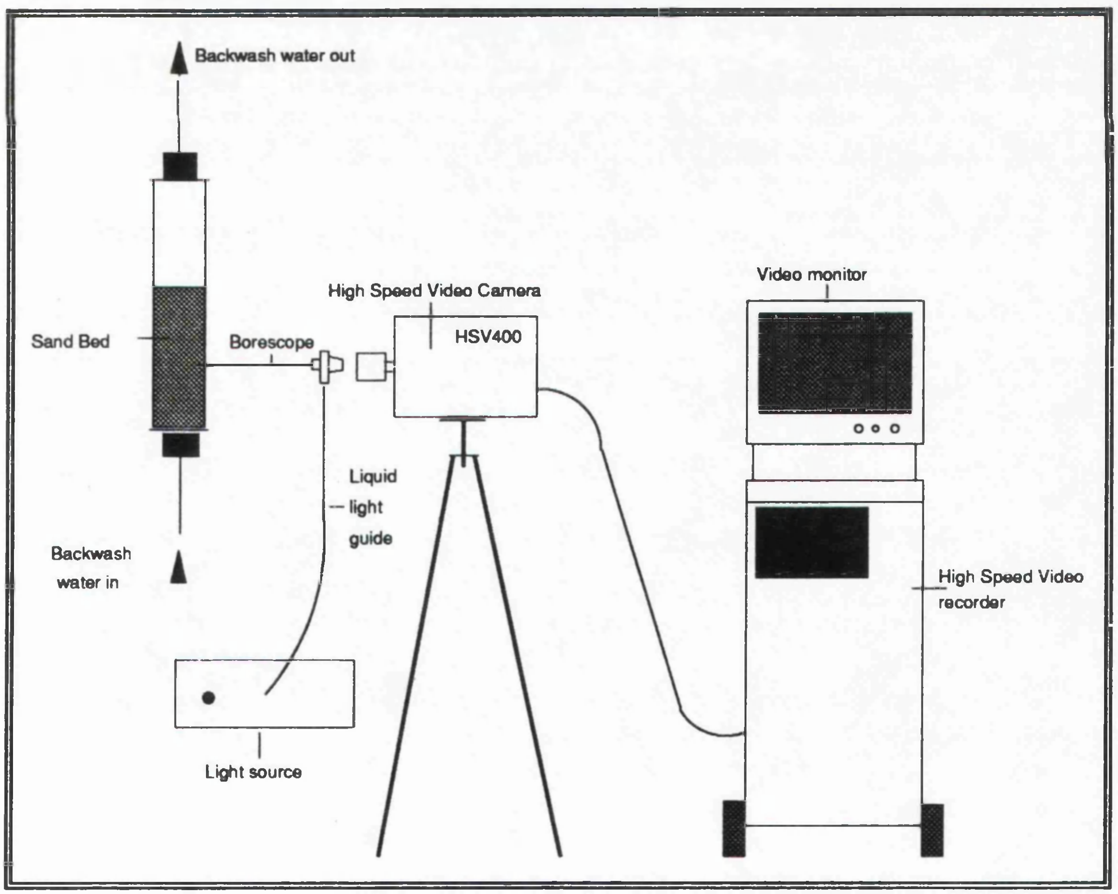


Fig. 3.4. High Speed Video recording setup; (a) photo, and (b) schematic.

3.6 Software Development

Software was written, using Microsoft QuickBasic, on the AT compatible personal computer. This was to perform two separate tasks:

(i) Communications

(ii) Velocity analysis

3.6.1 Communications Software

The communications line provides a two way link via the XY Coordinator: messages can be sent from the computer to the video equipment as control commands in a format that can be interpreted by the HSV, and data can be received from the HSV by the computer.

The XY Coordinator outputs from the HSV an ASCII string of characters which contains:

- the x and y coordinates of the cursor position
- the recorded time data in 3 groups: hundreds of seconds, seconds and milliseconds
- the scene code, which is set prior to recording a particular experiment
- status information, which may give an indication of unreadable frame information

Output of this data string can be controlled from the XY tablet or by the computer if programmed to do so.

Software in BASIC has been written (see Appendix I) to control the link between the computer and the HSV. Data output and frame advance commands are sent from the computer keyboard to the HSV. Four corner coordinates from the graticule, which represents a 1mm square, are taken for later calibration of the x and y measurements. The ASCII data string is read by the programme and deciphered before being written to a file containing 4 columns of data; x and y (in screen coordinates), t (ms) and scene code. This file is in a format that can be read by other programmes.

3.6.2 Velocity Analysis Software

Code has been written in BASIC (Appendix II) to read the x, y, and time data for a series of measurements for different grains, or detached dirt particles. Data is read from the file produced by the communications programme (see above) and the x and y coordinates are calibrated so that distances are in mm. Incremental velocities (mm/s) are calculated for each grain followed by the average for each grain and the average for *n* grains, in a given experiment. The variances for a set of velocities are also calculated. All the velocity data is written to a file.

Fig. 3.5. The NAC XY Coordinator

4 EXPERIMENTAL PROCEDURES

4.1 Evaluation of Optimum Optical Conditions for Video Recording

The optical and video equipment were evaluated prior to commencing experiments to ensure that the best possible image quality could be obtained. These evaluations were performed using Leighton Buzzard sand (light golden brown in colour) in the filter column.

Both 5mm and 8mm borescopes were evaluated for observation of the sand grains but only the 8mm borescope provided the necessary illumination for high speed video recording. New brass sleeves with plane glass windows were manufactured for insertion into the perspex column. Plane glass windows were chosen instead of plano-convex lenses as they would reduce the accumulation of deposits on the lens surface and also minimise optical distortion of the image. Previously, plano-convex lenses had been used in the filtration studies, described by Ives and Clough (1985), with the intention of improving magnification. Due to the fact that the convex surface of the lens was immersed in water the difference in refractive indices leads to minimal magnification (~1.01X) and only encourages the collection of deposits on the lens surface thereby obscuring the image. The magnification is provided by the combined borescope and camera lens systems and so a plane glass window is more suitable.

Different power light sources were evaluated as well as the effects of using the different gain settings (0, 6 and 12 dB) on the high speed video camera.
Use of the high speed shutter for recording was investigated as this could give very short exposure times (see previous chapter) which would enable freezing of the most rapid movements.

With the 250W light source set on maximum intensity it is possible to record at 200 and 400 pictures/sec without using any gain if the 8mm boresope is used. It is not possible to use a 5mm borescope with the HSV400 high speed camera. Obtaining enough illumination for recording using the high speed shutter remains a problem. For the 1/1000 sec shutter speed it is necessary to use the 6 or 12 dB gain available on the video camera which results in a noisy recorded image. This shutter speed is required for freezing some of the more rapid grain movements that occur under fluidisation conditions. The 1/2500 exposure can be used with 12dB gain but the picture lacks clarity and noise is a problem. It is not possible to use the highest shutter speeds giving 1/5000 and 1/10000 sec exposures.

Using the camera gain for low light situations reduced the signal to noise ratio. Use of the shutter appeared to further reduce it which could be due to the fact that video signals are only being received for a fraction of the time during which the frame is "exposed".

Experiments assessed the optical suitability of various filter media: Leighton Buzzard (L. B.) sand, Welsh NCB anthracite, granular activated carbon (GAC) and white Colorado silica sand. Different suspensions were tested with the two sands to obtain reasonable contrast between filter grains and deposits; these included white kaolin, dyed kaolin and terracotta modelling clay suspensions. The most optically suitable combination was Leighton Buzzard sand with kaolin suspension.

4.2 Backwashing of Clean Filter Sand

Experiments were conducted by backwashing a clean filter bed of Leighton Buzzard sand of two size ranges:

Sand size range	d_{10}	d_{60}	Uniformity Coefficient, $U_c = d_{60}/d_{10}$
0.5 - 1.0 mm	0.56 mm	0.76 mm	1.37
1.0 - 2.0 mm	1.03 mm	1.38 mm	1.34

Only the smaller sized sand (0.5 - 1.0 mm) was used for experiments with air scour.

Experiments were performed to determine the following:

1. Bed expansion and head loss behaviour for various water flow rates.
2. The minimum fluidising water velocity, V_{mf}.
3. Overall bed behaviour and individual grain behaviour during sub-fluidised, partially fluidised and fully fluidised states.
4. Bed and grain behaviour when air scour is introduced.
5. The air and water flow rates that give rise to collapse-pulsing.
6. The minimum flow rate and expansion required to release trapped air after air scour has stopped. This is essential for maintaining efficiency of subsequent filter runs.

Backwash water flow rates were measured using flowmeters, headloss over the entire bed was measured from manometers and expanded bed height was measured using a scale on the filter column wall. High speed video recordings of the sand grain behaviour were obtained during these experiments using the borescope.

4.3 Filter bed clogging

Kaolin and flocculated kaolin suspension were filtered, both made up in London tap water (conductivity = 600 µS cm^{-1}, pH = 8, total dissolved solids = 460 mg/l, ~ 80 - 100 mg/l Ca^{++} ions). The suspension supplied the constant head tank and filtered at a rate of ~ 3 m/h through a 62 cm deep, partially consolidated, bed of sieved (0.5 - 1.0 mm) L. B. sand. The porosity of the partially consolidated bed is 0.43. When the filter bed was clogged with an average deposit of ~5kg/m^2 the flow was turned off and the bed allowed to drain down.

The deposit density of ~5 kg/m^2 was achieved by filtering a concentrated suspension (640mg/l) for 150 min followed by 30 min while the suspension was being diluted with clear tap water, after which the constant head tank was allowed to drain down until the water level was 38 cm above the top of the sand bed. Dilution of the concentrated suspension was necessary to prevent the formation of a surface mat due to particle sedimentation between filtration and backwash. After trials with different concentrations and run times, this procedure gave optimum clogging of the bed for completion of filtration and backwash in one day.

Head loss through the sand bed was measured at the beginning, during and at the end of filtration for the experiments using the kaolin suspension. The nominal flowrate measured using the flowmeter was checked by timing the collection of a measured volume. For the flocculated kaolin suspension it was necessary to take more frequent head loss and flow rate readings during the filter run due to the more rapid filter bed clogging giving rise to an increased head loss with consequent reduction in flow. The filtrate was sampled occasionally to check for turbidity and/or suspended solids.

4.3.1 Details of suspensions

The first suspension was of light kaolin clay (particle size ranging from 0.8 to ~20 µm, with a mean size of 2.76 µm obtained using a Brinkmann particle size analyser, also Rajapakse (1988) has measured the size range using a Coulter Counter and obtains <1 to ~10 µm) in London tap water.

The second suspension was as above but additionally contained 80 mg/l of aluminium sulphate (alum) and 1 mg/l of Percol 155, a cationic polymer (i.e. positively charged). The alum and polymer dosages were determined from tests using a beaker and magnetic stirrer where concentrations were increased until adequate flocculation was observed.

4.4 Backwashing of the Clogged Bed

Backwashing took place within an hour of terminating filtration. The process was recorded on video tape by means of the borescope which viewed inside the sand bed through port 5, ~7 cm below the top of the bed. The video camera was recording at 200 frames per second for all the clogged bed experiments. Video recording was commenced just prior to opening the water and/or air valves. Backwash water was collected and samples analysed for average suspended solids concentration in a given volume. The temperature of the backwash water was noted for selected experiments.

The bed was further backwashed between successive runs to remove any remaining deposits and for the later experiments this included air scour at collapse-pulsing. The cleanliness of the bed was checked by visual observation of the emerging washwater and the bed itself, both externally and through the borescope, and by head loss readings taken at the beginning of each filter run.

Prior to backwashing the valve between the constant head tank and filter was closed, to prevent washwater from being lost to the supply tank, and the backwash outlet valve opened.

4.4.1 Water only backwash

Backwash water was supplied to the column from a cold water tank supplied with London tap water. A range of flow rates were used covering the static bed condition, partial and full fluidisation. The flow rate was controlled by a gate valve and measured using a flowmeter with a range from 2 to 22 l/min. The duration of the water only wash was varied according to the flow rate and was continued until the washwater appeared clean on leaving the column. Wash water was collected from the backwash outlet pipe in 25 litre containers. For the experiments with flocculated kaolin, some of the washwater passed through the turbidimeter but was later re-mixed with the appropriate washwater samples. During the backwash bed behaviour was noted and the expansion measured. Table 4.1 summarises these experiments.

4.4.2 Air/water backwash

The air and water wash experiments were designed to span the collapse-pulsing combination of air and water flow rates. A total of five experiments, with different water flow rates, were performed for each chosen air flow rate. The water flow rate was measured on a 1 to 10 l/min flowmeter; this range being

Expt. No.	Length of HSV recording (min.)	Water wash rate (m/h)	Duration of wash (s)	Clogging suspension[1]	Length of backwash turbidity record (s)	Notes
501	9.6	0 - 35.8	570	K	-	2
502	8.3	11.5 - 34.6	600	K	-	1
503	8	7.5	228	K	-	
504	7.5	6.9	249	K	-	
505	5	7.7	692	K	-	
601	12.5	8.9	596	K	-	
602	14.6	7.6	683	K	-	
603	6.7	9.6	1154	K	-	
701	24.5	8.1	1080	K	-	
702	6.7	8.5	1020	K	-	
801	6.7	15.0	692	K	-	
802	14.6	14.0	758	K	-	
803	17.2	11.5	900	K	-	
901	5	11.0	942	K	-	
902	11.7	16.9	621	K	-	
903	10.7	18.5	545	K	-	
904	8.3	14.0	750	K	-	
905	5	19.6	529	K	-	
111	8.3	25.6	401	K	-	
112	6.7	26.5	280	K	-	
113	6.8	30.6	339	K	-	
114	5.9	33.5	306	K	-	
115	3.3	39.0	275	K	-	
116	5.8	35.3	294	K	-	
117	5	40.3	257	K	-	
175	6.3	10.9 28.9	568 240	K+A+P	808	3
181	3	30.0	363	K+A+P	363	
187	2.4	26.5	411	K+A+P	411	
191	4.3	42.1	260	K+A+P	260	
192	4.1	44.4	245	K+A+P	245	

Table 4.1. Water only backwash experiments with a clogged bed.

1 K = kaolin; A = alum; P = Percol 155 (polymer). All in London tap water.

2 The water flow rate was gradually increased during this experiment to observe changes in bed and deposit behaviour.

3 The flow rate was increased to observe removal of remaining deposits in the second flush.

chosen to enable lower water rates to be used. The air plus water wash lasted for 5 min. followed by a water wash (9.7 l/min = 66 m/h) with the bed in the fluidised state, for 3 min..

Washwater samples were collected as before, the first sample covering the entire air/water wash, the remaining two for the fluidised water wash. Turbidimeter measurements were taken for nearly all the air scour experiments. A summary of the air scour experiments appears in table 4.2.

4.4.3 Mass balance techniques

From the backwash water collected in the 25 l containers, 0.5 l samples were taken to be used for suspended solids determination by drying to determine their weight. The volume dried was either 3 x 25 ml or 3 x 50 ml depending on the turbidity of the sample and the average value from the three samples used in the calculation of removal efficiency. All washwater samples were thoroughly mixed to ensure a uniform concentration prior to taking sub-samples.

4.4.4 Turbidity measurements

Initial trials evaluated the use of the Hach Ratio/XR flow-through turbidimeter for complete backwash turbidity records. It was found that the peak turbidity is always > 2000 NTU and so information on the peak shape above 2000 NTU could not be obtained. However, the turbidity record is useful for measuring the width of the peak and the shape of the tail as the turbidity decreases.

For the air scour and later flocculated kaolin experiments the backwash water was continuously sampled (at the same depth as the borescope for video observation, i.e. port 5) using the Hach flow-through turbidimeter set on the 2000 NTU range, and the analogue signal was recorded on a chart recorder. The start of backwash, termination of air scour and end of backwash were all noted on the chart recorder plot to enable turbidity measurements to be made. The flow rate through the turbidimeter was maintained at 0.2 l/min, although this was unsteady when air scour was being employed. The turbidimeter cell was cleaned routinely to prevent the build-up of deposits on the cell wall.

The peak turbidity of the washwater was above 2000 NTU for all experiments; the width of this peak was measured at the 2000 NTU line.

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1 Isokinetic sampling of the backwash water was not possible due to flowrate fluctuations, particularly during air scour.

Expt. No.	Air flow rate (m/h)	Water flow rate (m/h)[a]	Clogging suspension[b]	Notes
134	34.6	2.8	K	
128		6.9		*
133		9.8		*
132		11.5		*
135		13.8		
141	54.8	2.8	K	
142		6.9		
143		8.1		
164		10.1		
144		11.5		
145		13.8		
155	73.2	4.0	K	
146		4.6		
151		6.9		
152		9.2		
153		10.9		
154		13.8		
156	91.2	4.6	K	
157		5.8		

Expt. No.	Air flow rate (m/h)	Water flow rate (m/h)[a]	Clogging suspension[b]	Notes
161	91.2	8.1	K	
162		10.9		
163		10.4		
166	23	4.3	K	
171		6.9		
172		9.2		
173		10.9		
174		12.7		
182	34.6	9.2	K+A+P	
183		11.5		
184		13.3		
185		3.5		
186		4.6		
193	54.8	4.0	K+A+P	c
201		4.0		
194		5.8		
195		8.7		
196		11.5		
197		12.7		

Table 4.2. Air / water backwash experiments with a clogged bed.

a) All of these air scour experiments had combined air and water flow for 5 min, followed by 3 min of fluidised water wash at 56 m/h. The HSV record for all these experiments is for the 5 min of air + water wash only. Backwash turbidity was recorded throughout the 8 min, unless indicated by *.

b) K = kaolin; A = alum; P = Percol 155 (polymer). All in London tap water.

c) Poor run; no quantitative results, only video record.

5 RESULTS OF FILTER BACKWASHING EXPERIMENTS

5.1 Different Filter Media and Suspensions

As light levels are critical for high speed video recording it was important to obtain optically suitable combinations of filter media and suspensions. Leighton Buzzard sand provided the best video images for interpretation and was most suitable for use with kaolin as a clogging suspension. GAC and anthracite were unsuitable due to low light levels and highly reflective surfaces (causing glare) respectively. A whiter Colorado silica sand was tested, but gave a lower contrast image making analysis more difficult. Terracotta clay gave good contrast with Colorado sand which could not be used with kaolin due to similarity in colour. Dyed kaolin clay also gave good contrast but was not practical. Ferric chloride flocs also gave an unsatisfactory image. Darker suspensions reduce the light level in the video image.

5.2 Backwashing with Water Only

5.2.1 Clean bed behaviour

The nature of sand grain movement during the backwashing process was observed for varying water velocities, using Leighton Buzzard sand (d_{60} = 0.76 mm) and the results are summarised in Table 5.1. Video recordings were made at 200 frames/sec for all experiments.

Fig 5.1. shows the head loss and expansion curves for the above sand, from which v_{mf} = 23.1 m/h was determined by finding the intercept of straight lines drawn through the two different linear phases of each curve.

The results in table 5.1 are for a sand bed which had been allowed to come to rest after fluidisation and had not been artificially consolidated by agitation. A consolidated bed behaves differently until the bed is fully fluidised, as shown in fig 5.2., this is due to the lower porosity creating higher pore water pressures forcing bed expansion and grain movement to overcome any grain interlocking.

Temperature was measured when examining the clean bed behaviour and for backwashing of the clogged bed; it was found to vary between 14°C and 23°C . This variation occurred during single backwash runs due to the source of backwash water and the length of pipework through which it travelled prior to reaching the filter column. For some experiments the variation was less than this maximum encountered. The water temperature was never outside of this range. The temperature range will affect the bed behaviour as v_{mf} is related to the water viscosity which itself is temperature dependent and decreases with increasing temperature. For an increase in temperature from 14 to 23°C, the viscosity would decrease by ~20% having a similar effect on v_{mf}. Additionally for a clogged bed this would affect the fluid shear stresses acting on deposits.

Backwash rate (m/h)	% v/v_{mf}	Expansion (%)	Observations on overall bed behaviour	Borescope observations
< 11.5	< 50	0	No movement observed	No movement observed
11.5 - 13.9	50 - 60	0	Patchy surface activity develops, where finer fractions may be fluidised	
~ 17.0	~ 75	0	Small pockets of activity are seen within the bed, mainly around ports	grain movement is random and jerky at borescope tip, including flurries of grains
~ 20.8	~ 90	0.1	increased activity within the bed, finer fractions expand slightly	more movement
23.1	100 (v_{mf})	0.7	most of bed surface now agitated and more patches of activity seen through column wall	more intense activity - grains exhibit rotational and translational motion
> 23.1	>100		bed expands following typical pattern (see fig. 5.1) and all surface grains moving	grain movement is erratic, showing brief temporal and spatial phases of immobility followed by rapid movement and circulatory motion.
26.0		2.4	more expansion but still apparent dead patches	
28.9		4.5	whole bed appears mobile	very rapid movement, some may appear blurred on video screen
31.7		6.2	whole bed in motion - large scale circulation patterns set up (~ 10 cm)	"

Table 5.1. Behaviour of Leighton Buzzard sand (d_{60} = 0.76 mm) for different backwash water rates.

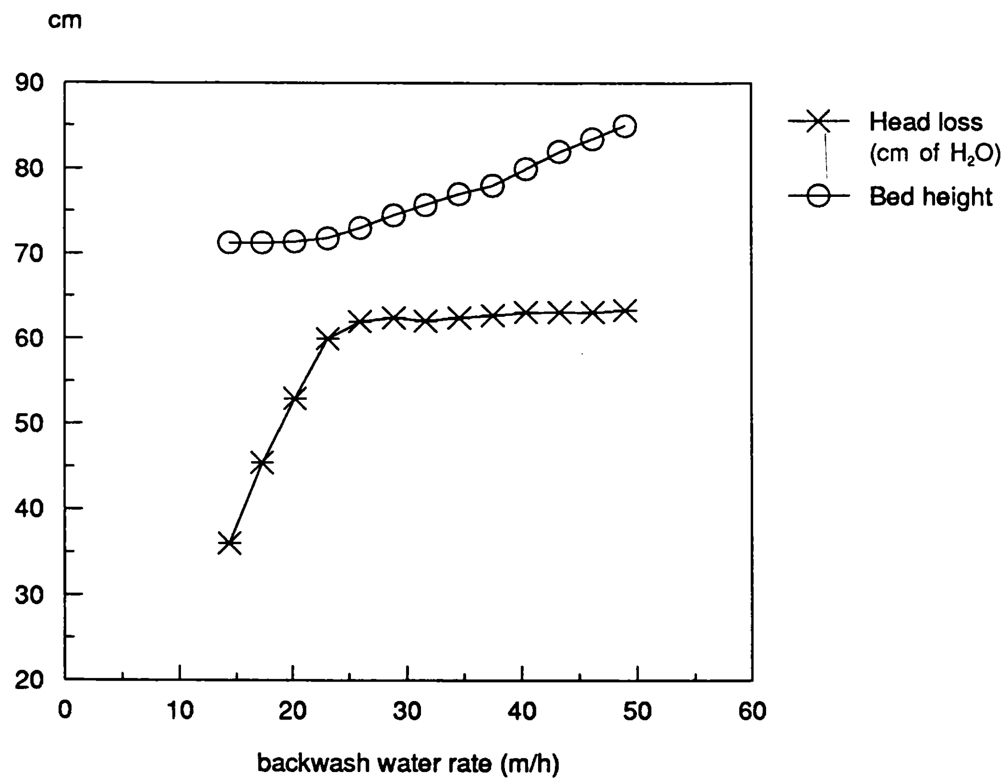


Fig. 5.1. Head loss and expansion curves for L. B. sand d60 = 0.76 mm.

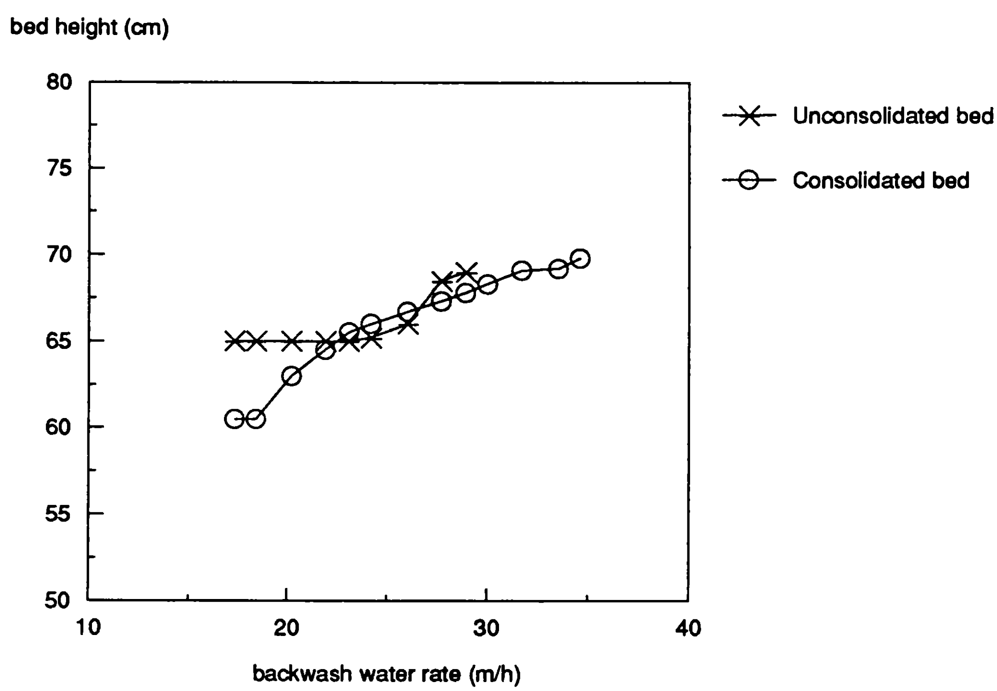


Fig 5.2. Expansion of consolidated and unconsolidated bed (L. B. sand)

The results indicate that there are three phases of the bed during water upflow, these can be summarised as follows:

Phase I — The grains are stationary as upflow is insufficient to overcome the grain weight and consequent effective stresses between grains

Phase II — Partially fluidised or transitional phase as fluidisation is approached; grains are intermittently mobile and rotate and move relative to each other (may result in abrasion) but are still in contact. Further increases in flowrate intensify these movements. Movement occurs in zones of higher flow possibly due to borescope insertions. Additionally, as the media consists of a range of sizes, the smaller fractions are fluidised for $v_w < v_{mf}$ (whole bed) and these are generally near the bed surface due to stratification during fluidisation. This effect is manifested as the curvature between the linear phases in fig. 5.1.

Phase III — Fluidisation; all grains are theoretically supported by upward fluid drag, the bed is in an overall steady state, but exhibits apparently random motions of grains or clusters of grains. There are intermittent periods of rest and vigorous motion due to local changes in the flow. Sand grains appear to collide but may only approach very closely, protected by a thin fluid film. Grain to grain contact is evident in immobile periods and may result in local abrasion which is insignificant in relation to fluid shear forces. As flow increases and the bed expands motion becomes more vigorous until there are no immobile phases.

The three phases can be seen on the accompanying video which is documented in Appendix III.

5.2.2 Kaolin clogged bed

The results for backwashing the kaolin clogged bed can be seen in Table 5.2. The deposits flushed out is a percentage of the calculated total retained during filtration. This was obtained from the average flow rate, the suspension concentration and the filter run time for each individual run. The flow rate was checked during the run and remained fairly constant ($\pm$0.01 l/min = $\pm$2%) for these experiments. It was found that the percentage of kaolin in the filtrate was negligible for all runs, although it is possible that occasional breakthrough may have occurred, resulting in small losses.

Fig. 5.3a shows a surface plot of the removal efficiency for various wash rates and durations. The surface was fitted to experimental data points which exhibit some scatter. Fig. 5.3b shows the surface after it has been through a smoothing operation which averages neighbouring grid points on the original surface, derived from the raw data. From the three dimensional plot it may be possible to select a required backwashing efficiency and then find the optimum combination of velocity and duration of wash for design purposes, depending on whether least cost, least energy or least water is the main criterion.

It can be seen that for kaolin ~50 % or more of the deposits can be removed for flow rates as low as 7.5 m/h, if the bed is washed for a duration of 12 minutes. Similarly, up to 80 % of deposits may be flushed out for flow rates of ~10 m/h after 15 minutes of washing. When backwashed with a water upflow rate sufficient for fluidisation of the sand grains, ~90 % of deposits may be removed at flow rates around the minimum fluidising velocity (v_{mf} = 23 m/h) if the bed is washed for 9 minutes.

Mass balance results of 100 % or more were never obtained, indicating a possible loss of suspension somewhere in the experiment. Some kaolin may be lost in the filtrate and there may be errors in the sampling of wash water and in the calculations based on the input suspension. The errors should, however, be consistent between runs so valid comparisons could be made. The maximum error is estimated to be a maximum ~10%, calculated from the scatter in the data. Possible sources of error include:

clogging flow rate (2 %)
suspension concentration (1 %)
losses in filtrate (1 %)
sampling of the backwash water due to poor mixing (~2 %)
errors in drying and weighing of backwash samples (1 %)

Internal and external observations on the filter bed indicated that the clogged bed behaves in a different way from the clean bed as backwashing commences. This is due to the deposits reducing the porosity and possibly providing some cohesion between filter grains. As backwash flow starts, even at very low velocities, the top few cm of the bed move as deposits are broken up and dislodged and some slight expansion may occur (< 1 cm), the bed then settles to its original height until the flow rate is increased sufficiently so as to cause expansion. Borescope and HSV observations reveal that many deposits are detached while the valves are being opened, and the flow is reaching its prescribed rates. The initial reversal of flow with washwater detaches deposits by water shear forces well below v_{mf}. Significant amounts of deposited kaolin are flushed out without fluidising the bed.

Expt. No.	HSV recording (min. real time)	Backwash Water Flow Rate m/h	%V/V_{mf}	Time of Wash (s)	% of Deposits Flushed Out	Notes
501	9.6	0 - 35.8	0 - 156	570		[1]
502	8.3	11.5 - 34.6	50 - 150	600		[1]
503	8	7.5	32.6	228	41	
504	7.5	6.9	30.0	249	39	
505	5	7.7	33.5	231 692	36 56	
601	12.5	8.9	38.7	189 596	53 78	
602	14.6	7.6	33.0	228 683	36 55	
603	6.7	9.6	41.7	181 692 1154	49 71.8 72	
701	24.5	8.1	35.2	215 1080	51 70	
702	6.7	8.5	37.0	215 1020	53 79	
801	6.7	15.0	65.2	118 232 692	60 80 97	
802	14.6	14.0	60.9	135 260 758	62 80 90	
803	17.2	11.5	50.0	149 301 900	56 77 85	
901	5	11.0	47.8	157 942	60 96	
902	11.7	16.9	73.5	103 207 621	60 80 89	
903	10.7	18.5	80.4	93 190 545	66 85 93	
904	8.3	14.0	60.9	125 250 750	53 71 86	
905	5	19.6	85.2	88 176 529	57 76 87	
111	8.3	25.6	111.3	67 138 401	58 76 86	
112	6.7	26.5	115.2	65 128 280	65 81 89	
113	6.8	30.6	133.0	58 118 339	67 86 86	
114	5.9	33.5	145.7	51 104 306	69 88 91	
115	3.3	39.0	169.6	45 133 275	73 90 90	
116	5.8	35.3	153.5	94 195 294	89 94 95	
117	5	40.3	175.2	42 86 257	72 89 90	

Table 5.2. Results of water only backwash of filter bed when clogged with kaolin suspension.

1 Water flow rate was gradually increased to observe changes in bed and deposit behaviour.

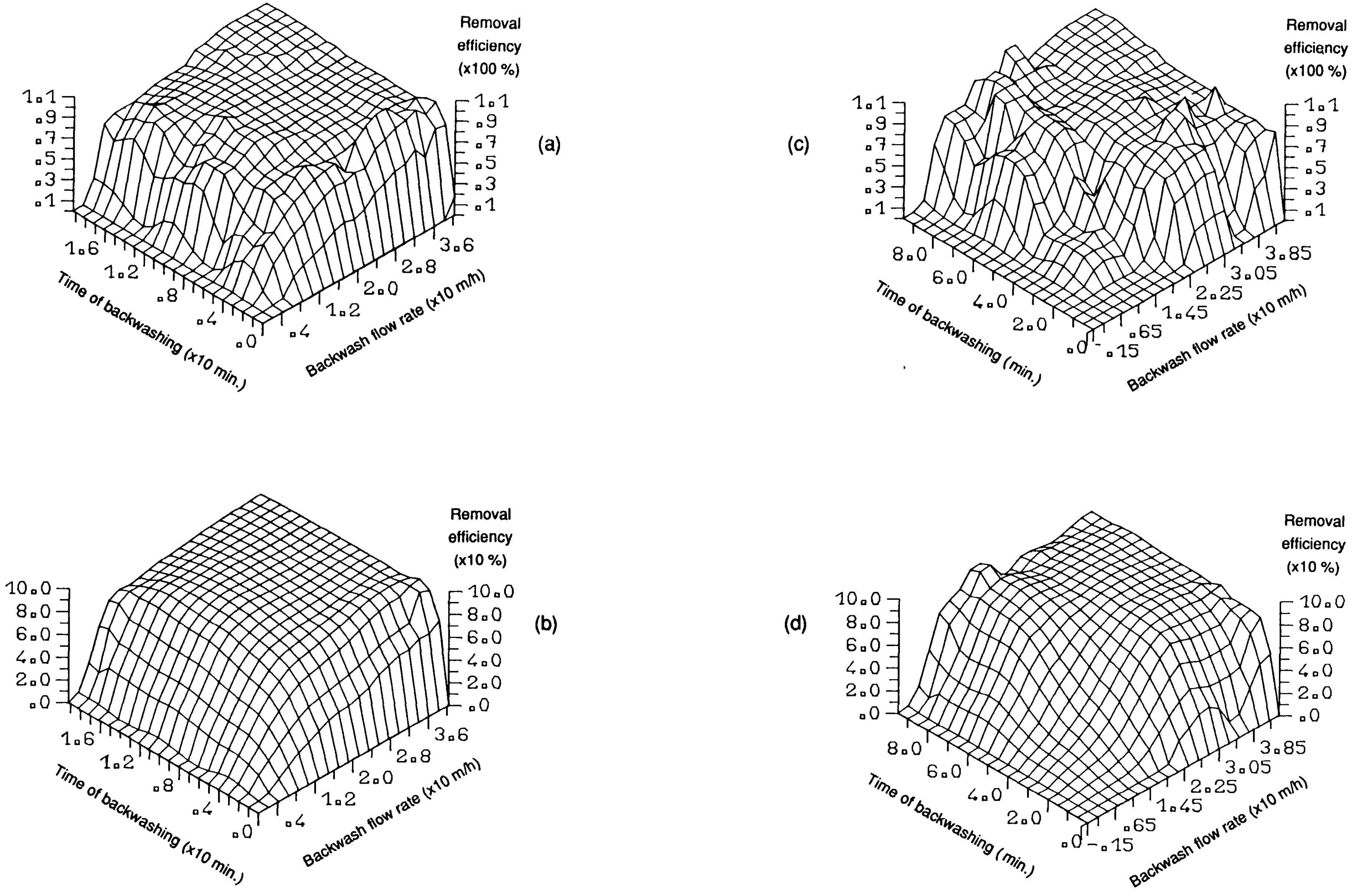


Fig. 5.3. Surface plots of removal efficiency for various water wash rates and durations: (a) surface fitted to raw data for kaolin clogging; (b) as (a) but surface plotted after smoothing operation; (c) surface fitted to raw data for kaolin suspension flocculated with alum and polymer; (d) as (c) but plotted after smoothing operation.

Another subfluidisation phenomenon was residual deposits undisturbed by the upflow in sheltered areas of pores where the water was virtually stagnant with consequent low shear stresses, or where the flocs have become trapped. However, when the grains moved, even with small relative motion, these sheltered areas became exposed to the flow with consequent shear and were removed, although some of the more adhesive deposits may remain.

During backwash, clouds of re-suspended detached deposits continuously flow past the end of the borescope restricting internal observation of grain behaviour and making particle tracking difficult. Therefore most observations were made at the very beginning of backwashing, which was when the majority of deposits are detached.

5.2.3 Kaolin with alum and polymer clogging

The results for backwashing the bed when clogged with kaolin suspension flocculated with alum and polymer (Percol 155) can be seen in Table 5.3. The mass balance information is complemented by information obtained from the turbidity record which had not been obtained for the kaolin only experiments. To calculate the mass of deposits retained in the bed for the flocculated suspension the average flow rate was obtained from a plot of a series of flow rate checks obtained during the filter run by collecting the volume of filtrate produced in a given time. The flow rate decreased during the run as the bed became clogged and the head loss increased as a result. This was very noticeable unlike the runs using kaolin only suspension of the same concentration.

A typical turbidity record (experiment 192) for these experiments is shown in fig. 5.4., from which the width of the peak at the 2000 NTU mark (t_{2000}) and the final turbidity (t_f) were read and the results recorded in table 5.3. It can be seen that there is a slight time lag (~20 s) between the start of wash and the arrival of washwater containing deposits at the turbidimeter; this is an effect of the length of tubing between the sample port and the turbidimeter cell. All turbidity records for water only wash have the same characteristic shape. The peak was narrow for expt. 175 because many deposits were still trapped within the bed as the wash rate was well below v_{mf}. There is not sufficient reliable turbidity data for this set of experiments to draw conclusions but comparison can be made with the air scour experiments using the same suspension (see section 5.3.3).

Expt. No.	HSV recording (min. real time)	Backwash Water Flow Rate		Time of Wash (s)	% of Deposits Flushed Out	Time turbidity[3] > 2000 NTU	Final turbidity[3]	Notes
		m/h	%v/v$_{mf}$			t_{2000} (s)	t_f (NTU)	
175	6.3	10.9 28.9	47.5 125.7	189 179 568 +240	21 71 75 +11	47	0 18	[1]
181	3	30.0	130.4	61 125 363	66 83 88	47	6	
187	2.4	26.5	115.2	72 143 411	66 82 83	100 est'd	10	[2]
191	4.3	42.1	183.0	53 90 260	68 80 82	76	8	
192	4.1	44.4	193.0	43 86 245	60 79 80	74	10	

Table 5.3. Results of backwashing filter bed clogged with kaolin suspension flocculated with alum and polymer.

Surface plots of removal efficiency have been obtained using the same techniques as for the kaolin clogged bed and can be seen in fig. 5.3c and 5.3d, displayed alongside the kaolin only results for comparison.

There are no marked differences in the shapes of the surfaces for kaolin only and flocculated kaolin and the total percentage removals are similar. Borescope and HSV observations indicate deposits are as readily removed when flocculated, but due to their more voluminous nature may be more easily trapped in pores unless the bed is fully fluidised.

5.3 Combined Air and Water Backwash

5.3.1 Clean bed behaviour

It was possible to observe air scour with the borescope and HSV setup and bubbles could be seen passing the borescope tip (see fig. 5.5).

1 The flow rate was increased to observe removal of remaining deposits in the second flush.

2 Paper jammed in turbidimeter chart recorder

3 See note 1 on p46.

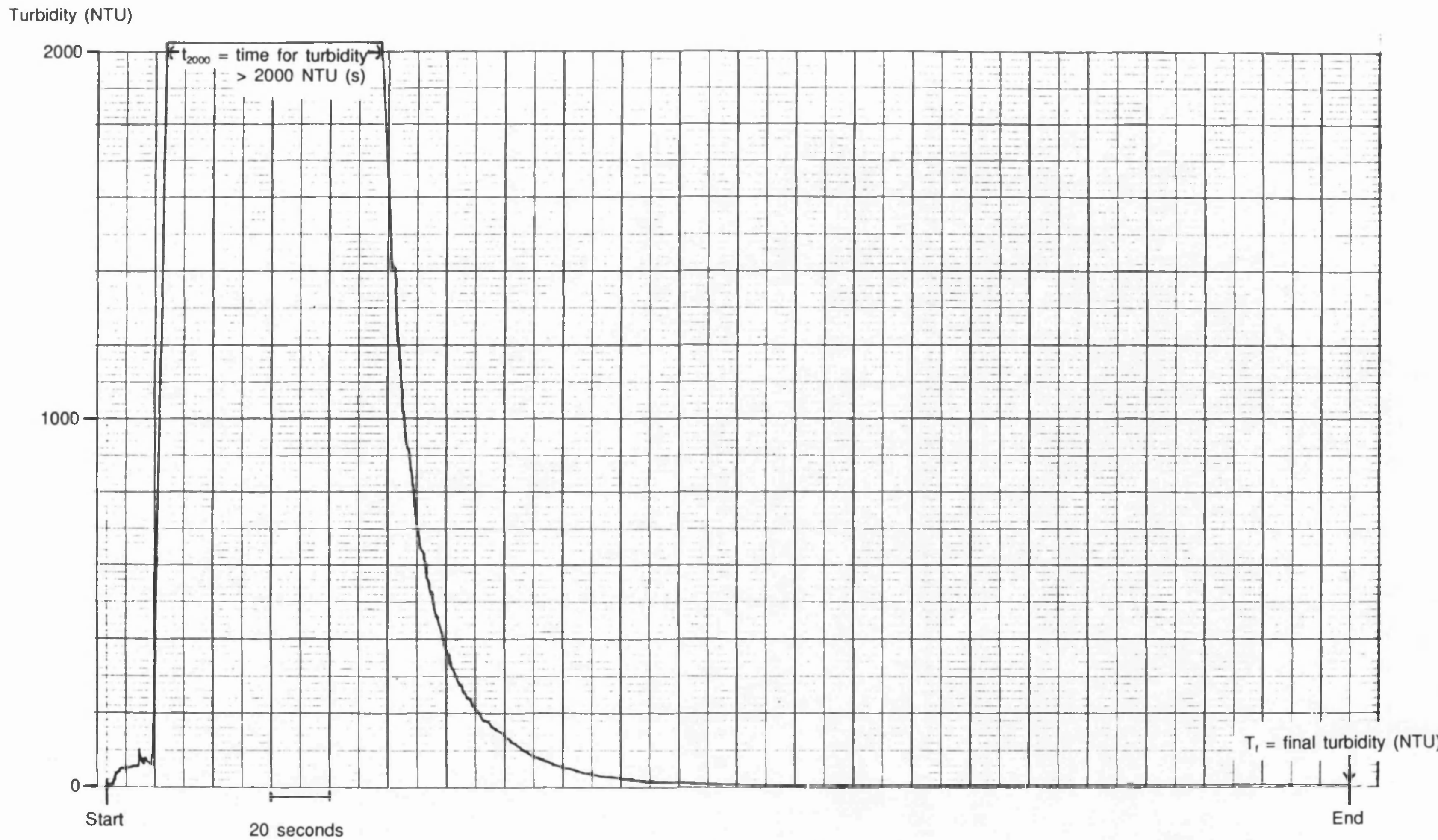


Fig. 5.4. Typical turbidity record (taken from expt. 192) for water only wash of bed clogged with flocculated kaolin suspension.

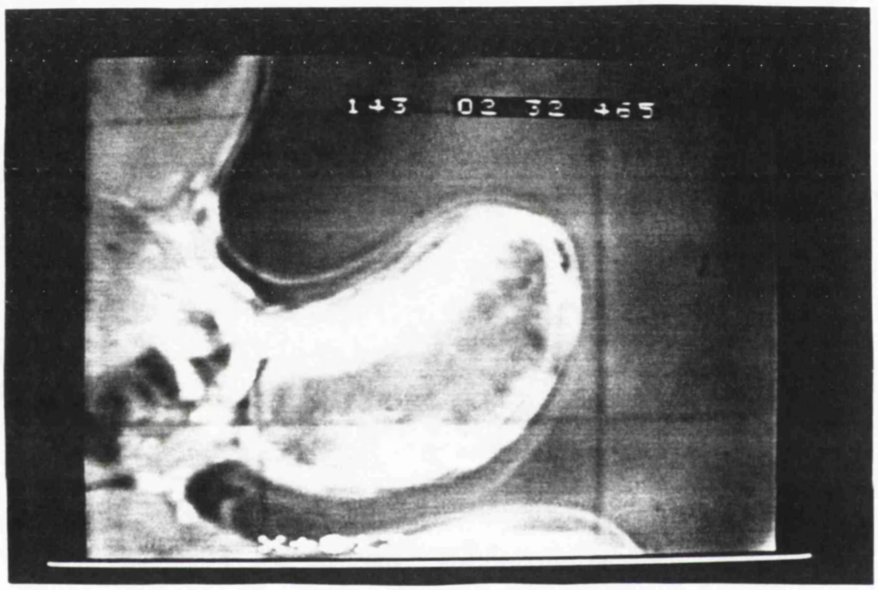


Fig. 5.5. Photo taken from HSV screen showing air passing borescope tip.

For constant air flow the following bed behaviour was observed when cocurrent water upflow was introduced:

Water rate ($\% \, v/v_{mf}$)	**Bed behaviour when air rate maintained constant (between 30 and 90 m/h)**
$v_w = 0$	Bed contracts. Surface layer pulsates in a vertical direction as bubbles erupt from the surface at several locations. The rest of the bed appears stationary when viewed through the column wall and air travels through the pores between grains. No circulation of the filter media. When viewed through the borescope (port 5, ~4 cm below the contracted bed surface) there are patches of activity as air passes through the field of view and motion appears oscillatory and occasionally vigorous. Surface activity becomes more vigorous and extends deeper into the bed as air flow rate is increased. Even at high air rates there is no overall circulation of the bed or cavity formation, although channels may form and collapse near the bed surface where effective stresses between grains are lower.
0 - 30	As water flow is introduced with the air scour then bed behaviour changes gradually. Air travels through the bed between grains but there is more bed pulsating activity and surface channels form to greater depth.
30 - 50	As water rate is increased then cavities begin to form and collapse at the base of the bed and the whole bed becomes more active with higher amplitude pulsations.
~ 50	Cavities are forming and collapsing throughout the depth of the bed causing the whole bed to pulsate and grains to circulate. This agrees with the observations of Amirtharajah (1984), who has termed this condition *collapse-pulsing*. Borescope internal observations showed an increase in grain activity as water flow is increased and the air rate maintained constant. At collapse-pulsing (40 - 50 % v/v_{mf}) grain movement is much more violent exhibiting rapid changes in magnitude and direction of grain velocity.
> 50	As v_{mf} is approached the air travels more freely through the bed by pushing the grains aside forming discrete channels. This results in less vigorous grain motion and less velocity changes

due to pulsation and collapse of air pockets. Eventually the whole bed becomes fluidised and the air moves freely through the bed without agitating the grains.

Grain velocity measurements made for the different combinations of air and water flow rates are described in chapter 6.

Bed expansion and contraction behaviour during air scour was examined and the results listed below in table 5.4.

Air flow rate (m/h)	Water flow rate (m/h)	Water flow rate % v/v_{mf}	Bed height (cm)	Contraction (% l/l_0)
0	0	0	64.0	100
34.6	0	0	58.0	90.6
34.6	5.8	25	58.0	90.6
34.6	7.2	31	58.2	90.9
34.6	8.7	38	58.5	91.4
34.6	10.1	44	59.0	92.1
34.6	11.5	50	59.5	93.0

Table 5.4. Bed contraction behaviour during air scour.

The final wash rate required to flush out trapped air after air scour was investigated by gradually increasing the backwash water flow rate. At around 3 l/min (17.3 m/h = ~75 % v/v_{mf}) most of the air appeared to be removed, when the bed was observed through the column wall, although some remained trapped right up to 8 l/min (200 % v/v_{mf}). This was in dead patches of the bed which may be due to poor washwater distribution and flow disturbances created by borescope insertion sleeves.

5.3.2 Kaolin clogged bed

Results of experiments can be seen in table 5.5. Turbidity measurements were made as for section 5.2.2 above, with an additional reading at the end of the air/water wash ($T_{a/w}$); a typical turbidity record can be seen in fig. 5.6..

The turbidity data, which gives an indication of cleaning efficiency, can be seen in fig. 5.7 and is plotted as surfaces along with removal efficiency in fig. 5.8. For combined air and water wash, with water flow less than v_{mf}, followed by a water wash (at greater than v_{mf}) experimental measurements indicate a maximum efficiency at air and water flow rate combinations satisfying the collapse-pulsing condition. In some cases efficiencies were high for water rates above the collapse-pulsing requirement but this means greater water usage for no improvement in cleaning, therefore the optimum appears to be around collapse-pulsing.

The data on cleaning efficiency in terms of % removal, obtained by mass balance techniques has little value in the air scour experiments as this is the total removed during the complete wash cycle which includes a water wash at 56 m/h for 3 min. (23 % expansion). The data for water wash alone indicates a removal efficiency of > 90 % for this rate and duration so any deposits remaining after the air/water wash should be flushed out. Data was also obtained on % removal during the air water wash but due to the variations in water rate for these experiments this also has little meaning. Higher water rates will flush out more of the detached deposits more quickly, but then there will be a dilution effect as a larger volume of water will be collected during this cycle of the wash. When the percentages were divided by the volume collected then the removals came out about equal but the turbidity data, in particular t_{2000}, indicates that for collapse-pulsing the peak is sharper.

The maximum efficiency, in terms of deposits washed out is similar to that obtained for water only wash, i.e. ~90 % solids removal (maximum achievable under these experimental conditions - see section 5.2.2) for a comparable water volume. This volume was calculated from the rates and durations used in the experiments, where the final water wash was at a rate of 56 m/h for 3 minutes. It is possible to reduce the volume of water used in the subsequent water wash by either reducing the flow rate, as ~23 m/h should be adequate, or the duration.

Borescope and HSV observations show that during the rapid grain movement while air scour is taking place deposits are detached very readily. Fluid shear forces caused by the general upflow and enhanced by the flow of pore water when displaced by air are responsible for most of the deposit detachments. Additionally there is grain contact and abrasion, especially during collapse-pulsing when overall bed circulation exposes more deposits to detachment forces. For water rates below that required to achieve collapse-pulsing there were patches within the bed where deposits remained trapped until released by the fluidising water wash.

Expt. No.	Air flow rate (m/h)	Water flow rate[1] (m/h)	Water flow rate[1] % V/V_{mf}	% of solids removed air/water wash	% of solids removed total	Time turbidity[2] > 2000 NTU, t_{2000} (s)	Turbidity[2] at end of air/water wash, $t_{a/w}$ (NTU)	Final turbidity[2] t_f (NTU)
134	34.6	2.8	18	34	66	140	118	15
128		6.9	30	56	82			*
133		9.8	42	76	97			*
132		11.5	50	66	79			*
135		13.8	60	77	86	138	500	8
141	54.8	2.8	18	23	88	146	180	23
142		6.9	30	54	80	101	83	26
143		8.1	35	63	67	98	82	37
164		9.2	40	61	79	99	60	30
144		11.5	50	71	86	124	144	41
145		13.8	60	71	78	147	90	22
155	73.2	4.0	18	45	85	181	540	36
146		4.6	20	>100	>100	123	310	29
151		6.9	30	58	97	105	131	30
152		9.2	40	65	87	90	68	29
153		10.9	48	69	81	109	86	31
154		13.8	60	73	81	154	155	21
156	91.2	4.6	20	44	78	245	600	52
157		5.8	25	51	81	171	159	10
161		8.1	35	59	79	141	75	8
162		10.9	48	67	79	142	110	48
163		13.3	58	71	80	182	281	30
166	23	4.3	19	33	69	177	240	28
171		6.9	30	49	83	140	100	16
172		9.2	40	49	66	128	65	13
173		10.9	48	67	80	121	80	17
174		12.7	55	63	72	143	170	16

Table 5.5. Results of combined air and water backwash of bed clogged with kaolin suspension.

1 All of these air scour experiments had combined air and water flow for 5 min, followed by 3 min of fluidised water wash at 56 m/h. The HSV record for all these experiments is for the 5 min of air + water wash only. Backwash turbidity was recorded throughout the 8 min, unless indicated by *.

2 See note 1 on p46.

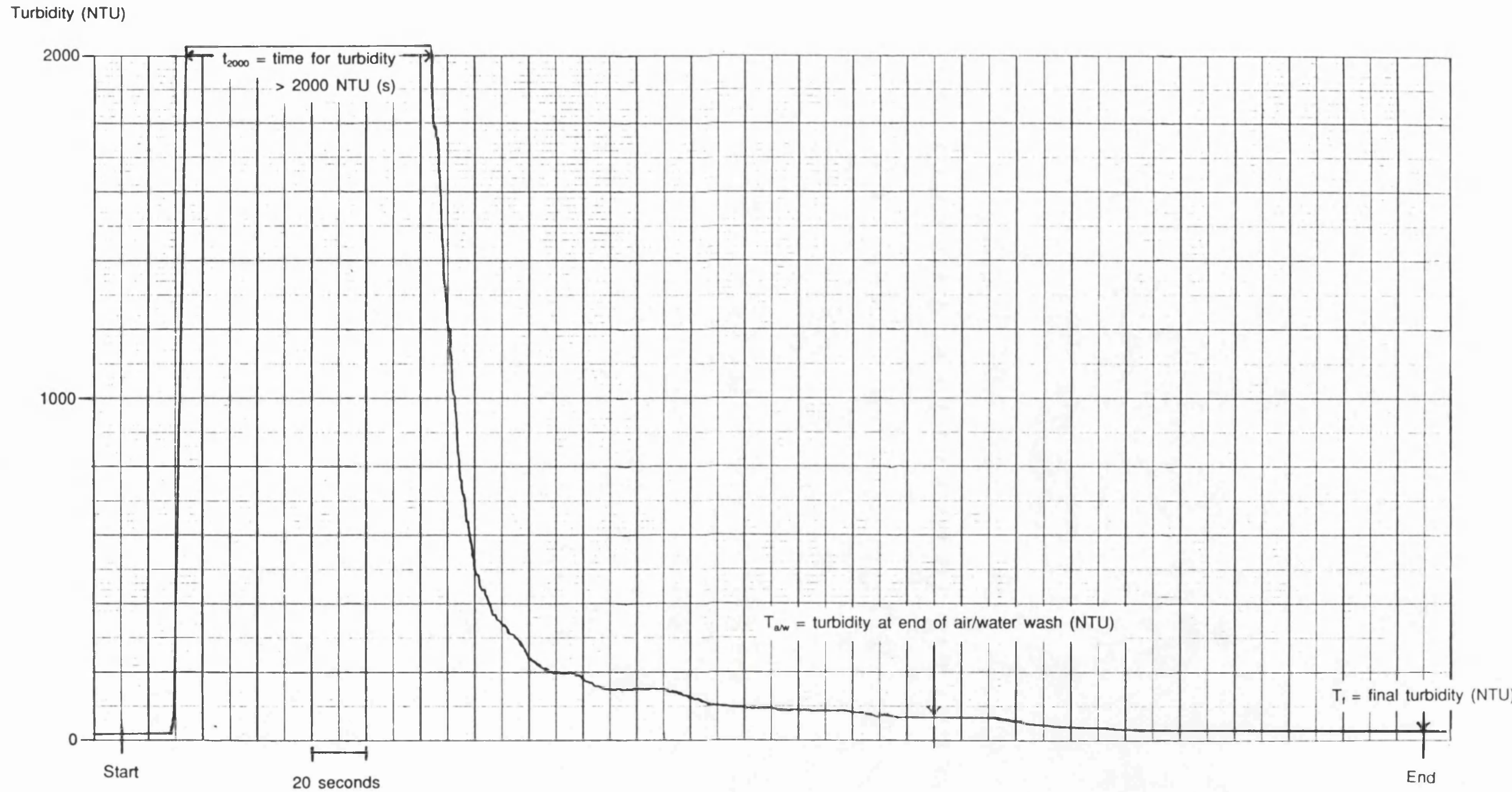
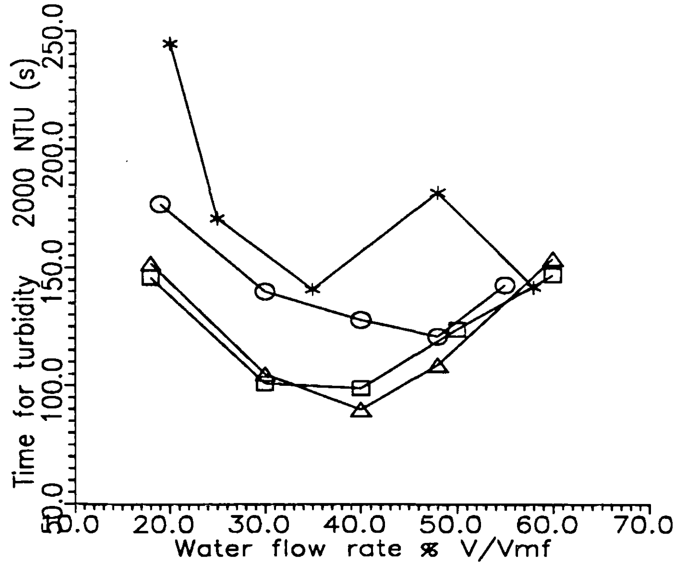
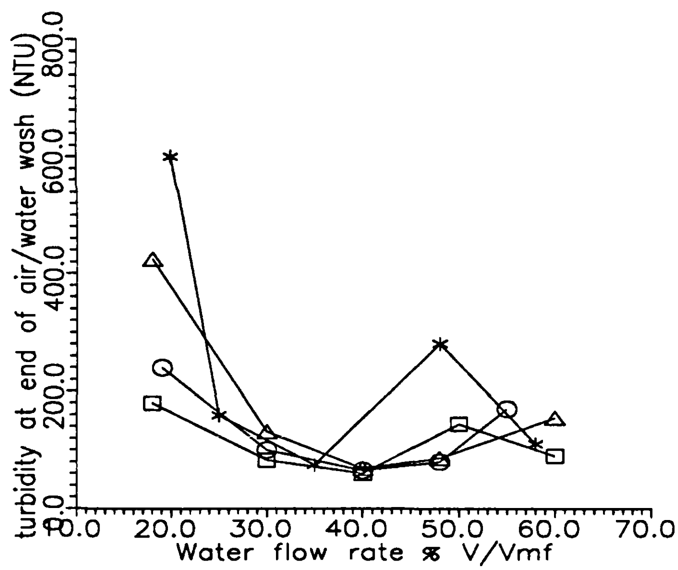


Fig. 5.6. Typical turbidity record (taken from expt. 152) for backwash sequence of 5 min. air + water, follwed by 3 min. high rate water flushing.





Key

o v_{air} = 23 m/h	Δ v_{air} = 91 m/h
- v_{air} = 55 m/h	* v_{air} = 73 m/h

Fig. 5.7. Turbidity data for air + water wash.

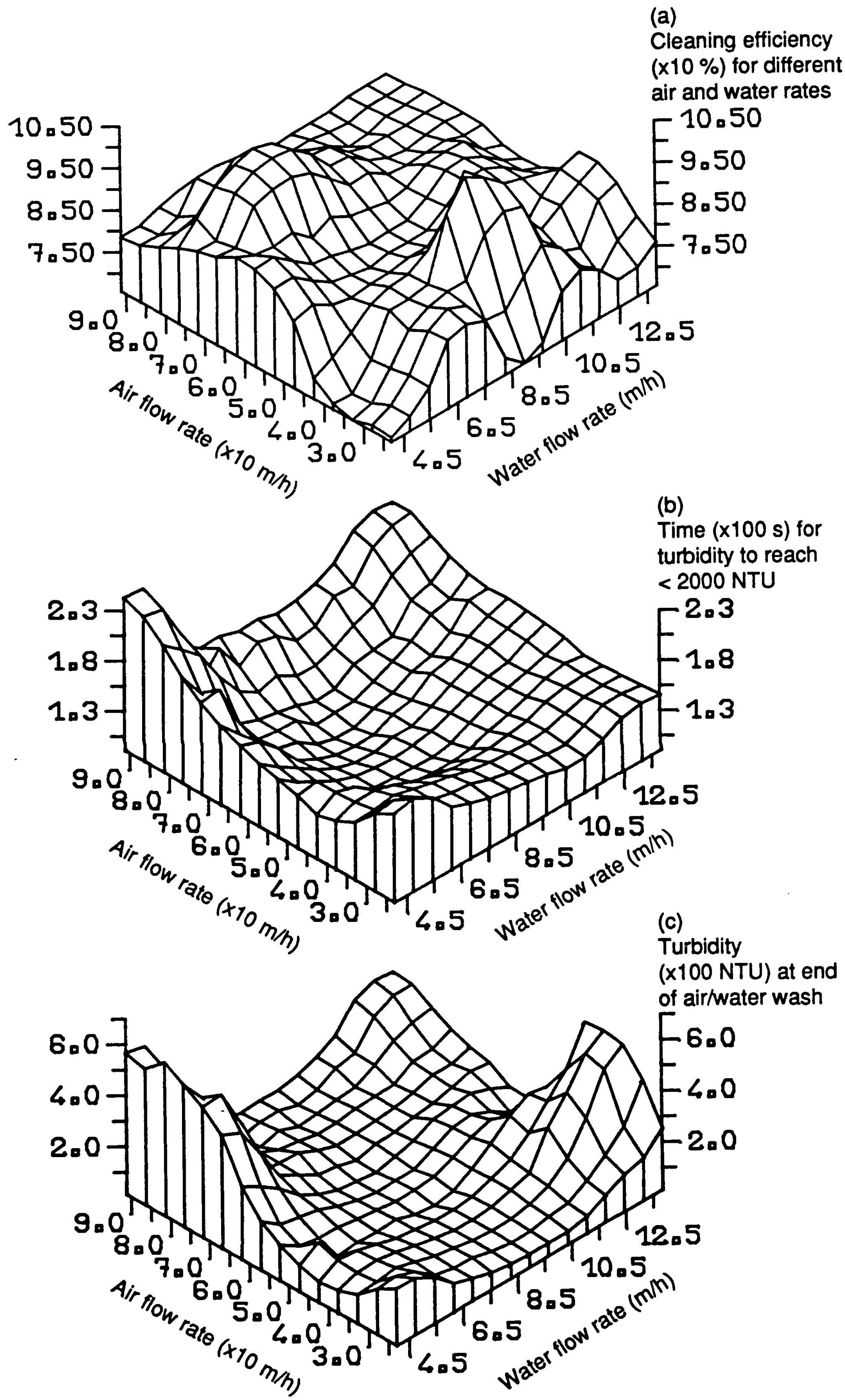


Fig. 5.8. Surface plots of removal efficiency and turbidity data for air + water wash of kaolin clogged bed.

After 1-2 minutes of simultaneous air and water flow at collapse-pulsing, the grains appear clean and the subsequent fluidising water wash serves to flush out the remaining dislodged deposits from within the bed. It appears that the 5 minute air/water wash was not necessary for removal of the kaolin deposits. In all cases grains appeared clean at the end of 5 minutes.

The data indicates that an air water wash for 2.5 - 3 min at collapse-pulsing would be sufficient to dislodge all deposits, followed by a fluidising water wash between v_{mf} and $2v_{mf}$ to flush out remaining deposits and trapped air.

5.3.3 Kaolin with alum and polymer clogging

Results for these experiments can be seen in table 5.6 which were obtained in the same way as for those described in section 5.3.2. Graphs of the turbidity data are shown in fig 5.9. The data exhibits similar trends to those of the kaolin only experiments in that there appears to be an optimum around collapse-pulsing. Fig 5.10 shows the data for the flocculated suspension compared with that for the kaolin only suspension for an air rate of 54.8 m/h. The differences between the data, i.e. the kaolin suspension appears to have wider turbidity peaks, may be due to their different adhesive properties but are more likely due to the differences in the particle size distributions, which affects the turbidimeter readings.

The borescope observations give no indication of any difference in adhesiveness of deposits. However, they do show that deposits are detached as larger flocs which have a greater tendency to become trapped between grains until the subsequent fluidising water wash.

Expt. No.	Air flow rate (m/h)	Water flow rate[1]		% of solids removed		Time turbidity[4] > 2000 NTU	Turbidity[4] at end of air/water wash	Final turbidity[4]	Notes
		(m/h)	% V/V_{mf}	during air & water wash	total	t_{2000} (s)	$t_{a/w}$ (NTU)	t_f (NTU)	
182	34.6	9.2	40	64	79	85	68	12	
183		11.5	50	67	79	90	80	20	
184		13.3	60	78	88	72	100	5	
185		3.5	15	34	73	116	110	11	
186		4.6	20	42	75	79	42	29	
193	54.8	4.0	18	89	94	115	360	12	2
201		4.0	18	41	86	118	240	7	
194		5.8	25	58	86	120	135	29[3]	
195		8.7	38	67	86	75	45	3	
196		11.5	50	76	88	96	55	5	
197		12.7	55	70	78	80	110	3	

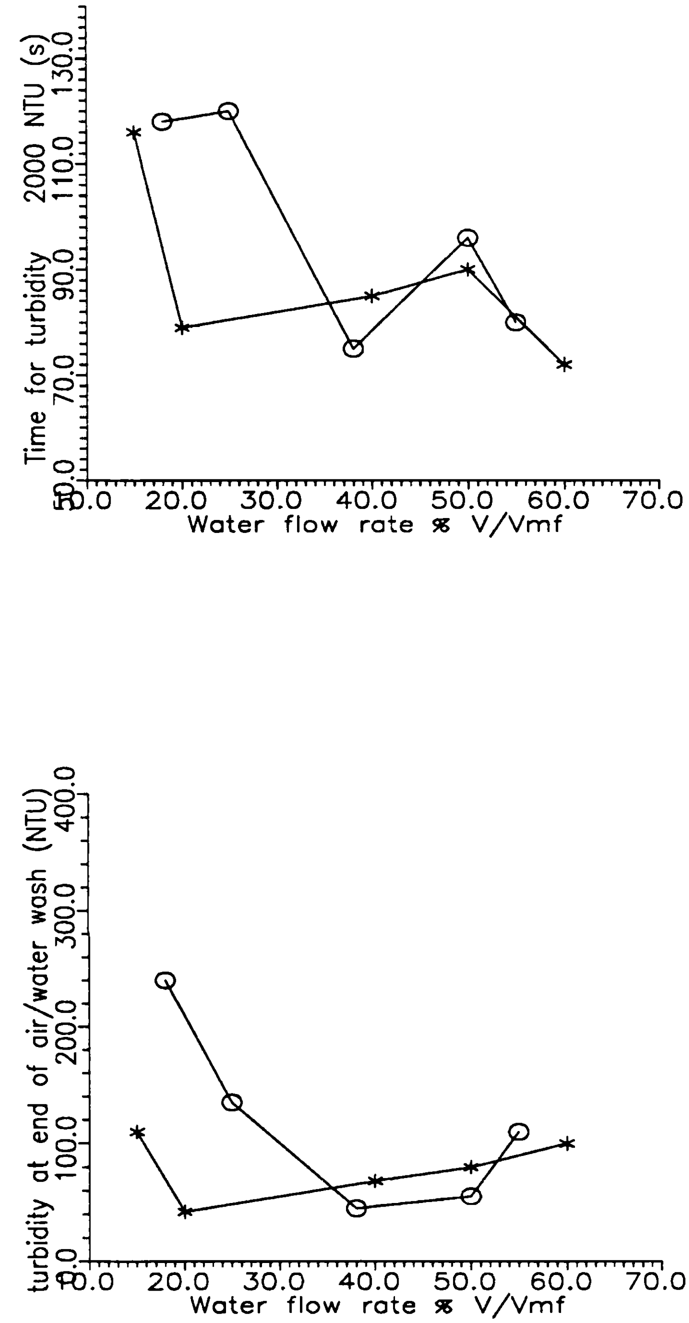
Table 5.6. Results of combined air and water backwash of bed clogged with kaolin suspension flocculated with alum and polymer.

1 All of these air scour experiments had combined air and water flow for 5 min, followed by 3 min of fluidised water wash at 56 m/h. The HSV record for all these experiments is for the 5 min of air + water wash only.

2 Poor run; unreliable quantitative results, only video record.

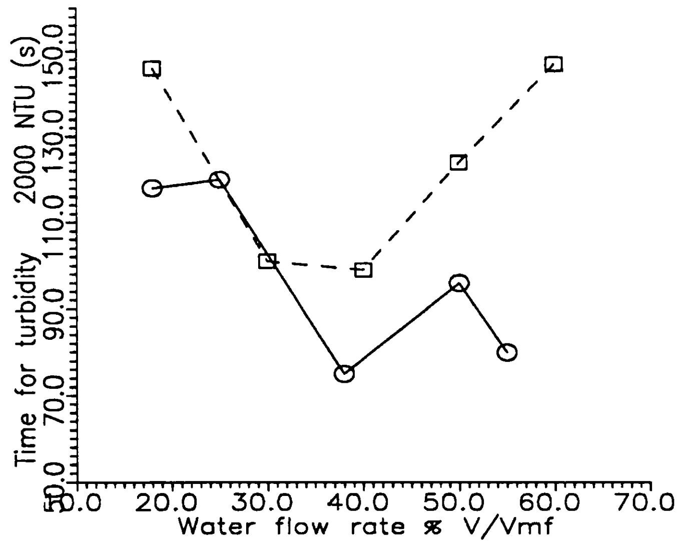
3 Turbidimeter cell dirty

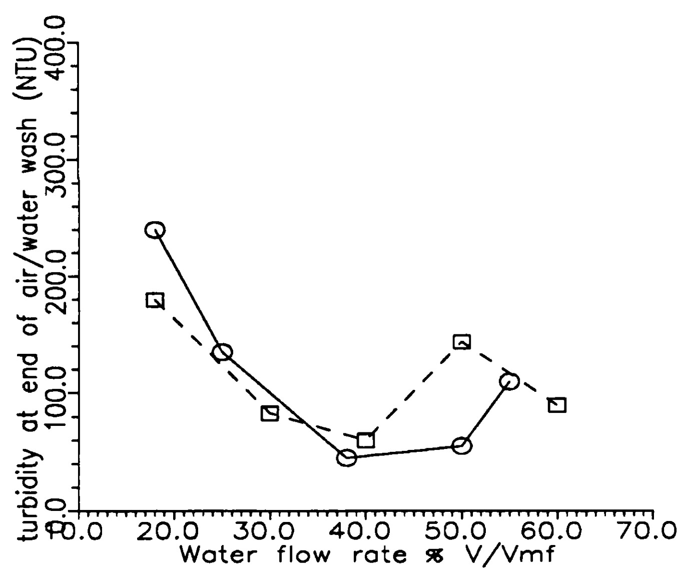
4 See note 1 on p46.



<u>Key</u> * V_{air} = 35 m/h o V_{air} = 55 m/h

Fig. 5.9. Turbidity data for air + water wash of kaolin flocculated with alum and polymer clogged bed.





<u>Key</u> - kaolin only o flocculated kaolin

Fig. 5.10. Comparison of turbidity data for air + water wash of kaolin and kaolin flocculated with alum and polymer clogged bed.

6 COMPUTER IMAGE ANALYSIS

6.1 Methods and Computer Code

The data transfer software (Appendix I) communicates between the PC and HSV so that the PC can receive x, y, time and scene code data from the video recordings. Additionally frame advance is controlled by commands from the PC keyboard.

Measurements were taken for 10 randomly chosen sand grains for each experiment. Random selection of grains was obtained by fast-forwarding the tape then stopping it in a random position, choosing a suitable grain for measurement, then measuring its position using the pen and tablet of the XY coordinator. Measurements continued as frames advanced until the grain left the field of view, when the tape was forwarded to commence the next set of measurements.

All measurements were done in the latter half of the backwash cycle when most deposits had been flushed out. This was necessary to ensure a clear image of the grains for tracking purposes, which were obscured by clouds of kaolin deposits in the early part of the wash. In the case of the combined air and water experiments this was still done during the combined wash phase.

It was not possible to track individual kaolin particles or flocs as they were obscured by the clouds of kaolin being flushed out. Occasionally, at the start of the wash, individual flocs can be seen at low flow rates while valves are being opened. Therefore measurements could not be related to the backwash rate and theory for pore velocities and so have very little value.

The velocity analysis software (Appendix II) calculates instantaneous velocities from the above data; velocities in the x and y directions are calculated, followed by the magnitude and direction of the resultant vector velocity. The magnitude of the velocity vector was used for all subsequent statistical calculations. The mean, variance, maximum and minimum were found for each grain and then the overall mean, variance, median, maximum and minimum for all 10 grains were obtained. Velocities of grains are in mm/s as these are appropriate units when measurements are taken from video material (1 mm/s = 3.6 m/h).

Relative frequency polygons of the velocity distributions for each experiment were obtained using a standard PC software package, which allowed selection of the bin size for frequency calculations. Unfortunately, all plots have been scaled in the vertical direction according to their individual maxima making visual comparison of peak heights difficult; the values can still be read from the axes, however.

6.2 Results

Results of the velocity measurements are shown in tables 6.1 and 6.2, which are for water only backwash and combined air/water backwash experiments, respectively. For some data sets (experiments 901, 903 and 904) the sample size was too large for all parameters to be calculated, with the software employed.

The relative frequency polygons of the velocity distributions are shown in figs. 6.1 to 6.6. Fig. 6.7 shows surface plots of the velocity data which can be compared with fig. 5.8; the velocity data exhibits a clear ridge of maxima in the same position as the minima in the turbidity data. These correspond to collapse-pulsing and indicate maximum cleaning efficiency for these flow rate combinations. The data from which the surfaces were obtained can be seen in table 6.2.

The velocity data for water only wash shows a general relative increase in observations at higher velocities with increasing flow rate as well as a increase in the modal velocity. The water only backwash velocity distributions display a bimodal tendency. This could be due to the occurrence of low activity and rapid flurry phases which have been observed through the column wall and borescope.

For the combined air/water wash experiments there appears to be an optimum (i.e. more higher velocities as well as a shift in the mode) around collapse-pulsing. The velocities obtained for combined air/water wash indicate that high grain velocities, with consequent high fluid shear stresses and increased grain collision energy, can be obtained for very much lower water rates representing a saving in clean water usage. If experiments 112 (fluidised bed) and 152 are compared it can be seen that higher velocities are obtained for just over one third of the water flow rate. These higher grain velocities indicate a higher kinetic energy of the grains which should lead to more violent collisions and increased fluid shear forces on grain surfaces. Additionally, fluid shear forces on grains will be greater for the same water rate when air is used due to the reduction in pore space due to bed contraction and due to air occupying some of the pore space.

Fig 6.6 shows the velocity distributions for air/water wash when the air rate was below that required to achieve collapse-pulsing and the lack of high velocities can be seen for all water rates, although there is still a general increase. All others (figs. 6.2 to 6.5) are within the range of application of the collapse-pulsing equation (Amirtharajah, 1984).

Expt. No.	Backwash Water Rate		Grain speed data (mm/s)					
	m/h	$\%v/v_{mf}$	Sample size	Minimum	Maximum	Median	Mean	Variance $(mm/s)^2$
901	11.0	47.8	-	0	5.0	-	.0092	.015
902	16.9	73.5	3278	0	20.0	.106	0.49	1.81
903	18.5	80.4	-	0	16.6	-	0.88	3.18
904	14.0	60.9	5679	0	14.9	-	0.23	0.58
905	19.6	85.2	2424	0	5.5	.059	0.15	0.11
111	25.6	111.3	184	0	33.3	8.0	8.9	40.0
112	26.5	115.2	198	0	19.9	7.2	7.7	16.6
113	30.6	133.0	138	2.9	43.9	14.6	14.3	40.8
114	33.5	145.7	98	1.4	34.9	12.2	14.1	60.0
115	39.0	169.6	73	7.5	36.2	21.2	21.7	55.6
116	35.3	153.5	146	0	51.3	13.2	13.3	74.6
117	40.3	175.2	83	5.2	80.0	22.3	24.8	215.8

Table 6.1. Velocity data for experiments with water only backwash at different flow rates.

$1\frac{m}{h} = \frac{m}{h} \times 10^3 \frac{mm}{m} \times \frac{1\ h}{3600\ s} = \frac{1}{3.6}\frac{mm}{s} \approx 0.3\frac{mm}{s}$

Expt. No.	Air flow rate (m/h)	Water flow rate		Grain speed data (mm/s)					
		(m/h)	% v/v_{mf}	Sample size	Minimum	Maximum	Median	Mean	Variance $(mm/s)^2$
134	34.6	2.8	18	1091	0	113.2	1.8	3.6	52.1
128		6.9	30	1995	0	41.3	1.1	2.6	15.0
133		9.8	42	466	0	136.4	5.3	7.3	112.6
132		11.5	50	450	0	58.5	3.4	6.4	74.2
135		13.8	60	222	0	133.7	6.4	9.2	200.2
141	54.8	2.8	18	661	0	73.3	1.7	5.5	78.8
142		6.9	30	389	0	188.1	3.9	8.2	191.7
143		8.1	35	-	0	155.5	-	11.1	-
164		9.2	40	161	0	100.3	7.2	11.0	227.9
144		11.5	50	141	0	97.3	14.0	17.6	235.3
145		13.8	60	182	0	104.2	7.0	10.3	147.9
155	73.2	4.0	18	1095	0	49.0	1.5	2.9	20.9
146		4.6	20	-	0	45.1	-	6.2	-
151		6.9	30	369	0	45.1	4.1	7.4	71.3
152		9.2	40	218	0	112.0	5.1	10.5	202.8
153		10.9	48	120	1.5	84.0	15.3	19.5	182.1
154		13.8	60	167	0	39.8	7.5	10.7	98.9
156	91.2	4.6	20	501	0	66.6	2.8	6.0	64.7
157		5.8	25	414	0	39.6	6.8	8.9	63.8
161		8.1	35	329	0	96.1	6.0	11.8	222.2
162		10.9	48	317	0	136.4	2.7	9.1	176.3
163		13.3	58	199	0	75.3	7.1	11.0	155.6
166	23	4.3	19	1467	0	58.3	0.7	2.0	13.5
171		6.9	30	871	0	58.1	1.4	3.2	28.2
172		9.2	40	614	0	73.9	3.3	5.6	70.7
173		10.9	48	460	0	55.6	3.3	4.8	33.4
174		12.7	55	175	0	102.8	7.2	10.3	131.4

Table 6.2. Velocity data for experiments using combined air and water backwash.

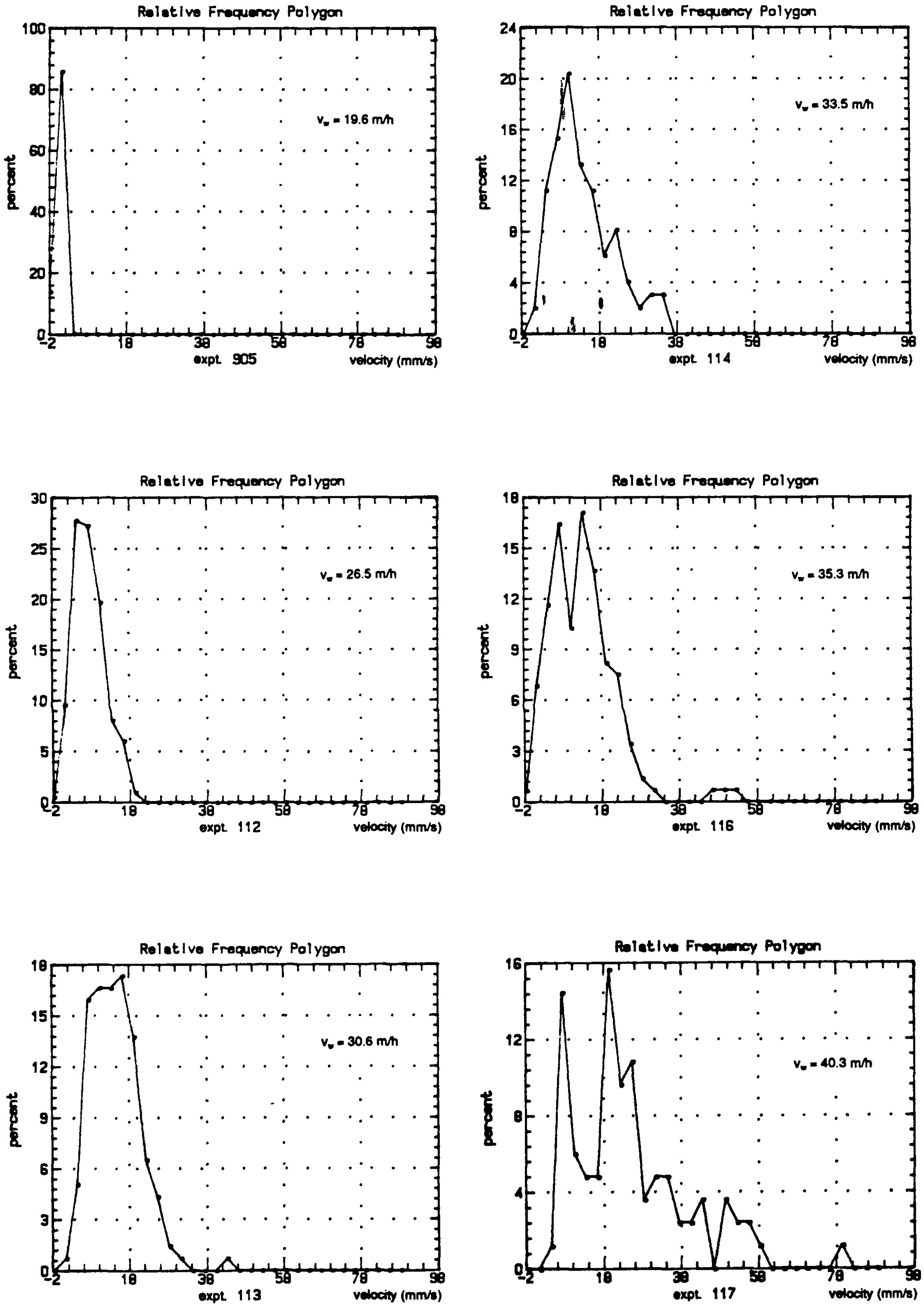


Fig. 6.1. Grain velocity distributions for water only backwash at various water rates (v_w). Bin size = 3.

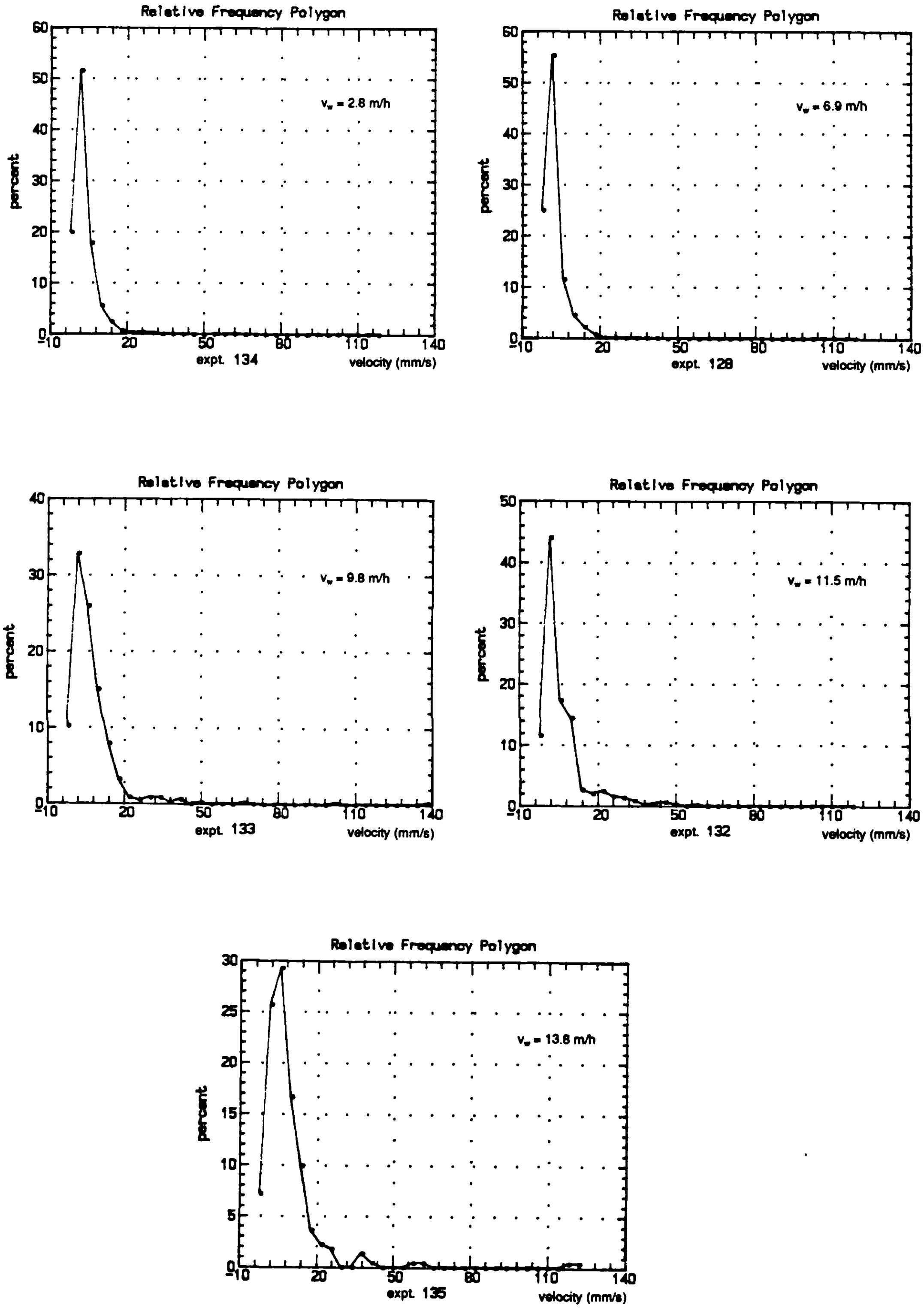


Fig. 6.2. Grain velocity distributions for air + water backwash for different water rates (v_w); air rate, $v_a = 34.6$ m/h. Bin size = 4.

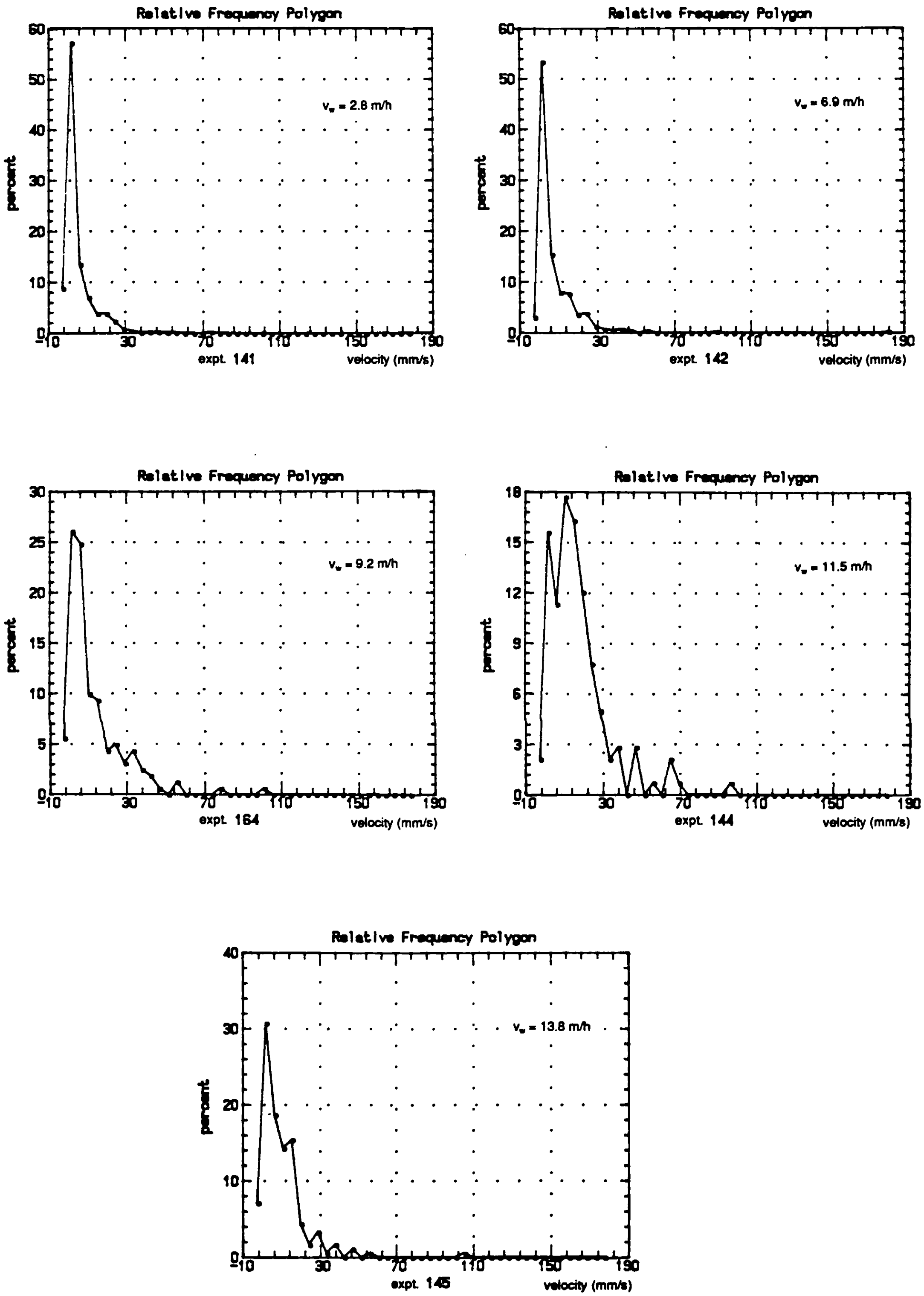


Fig. 6.3. Grain velocity distributions for air + water backwash for different water rates (v_w); air rate, $v_a = 54.8$ m/h. Bin size = 4.

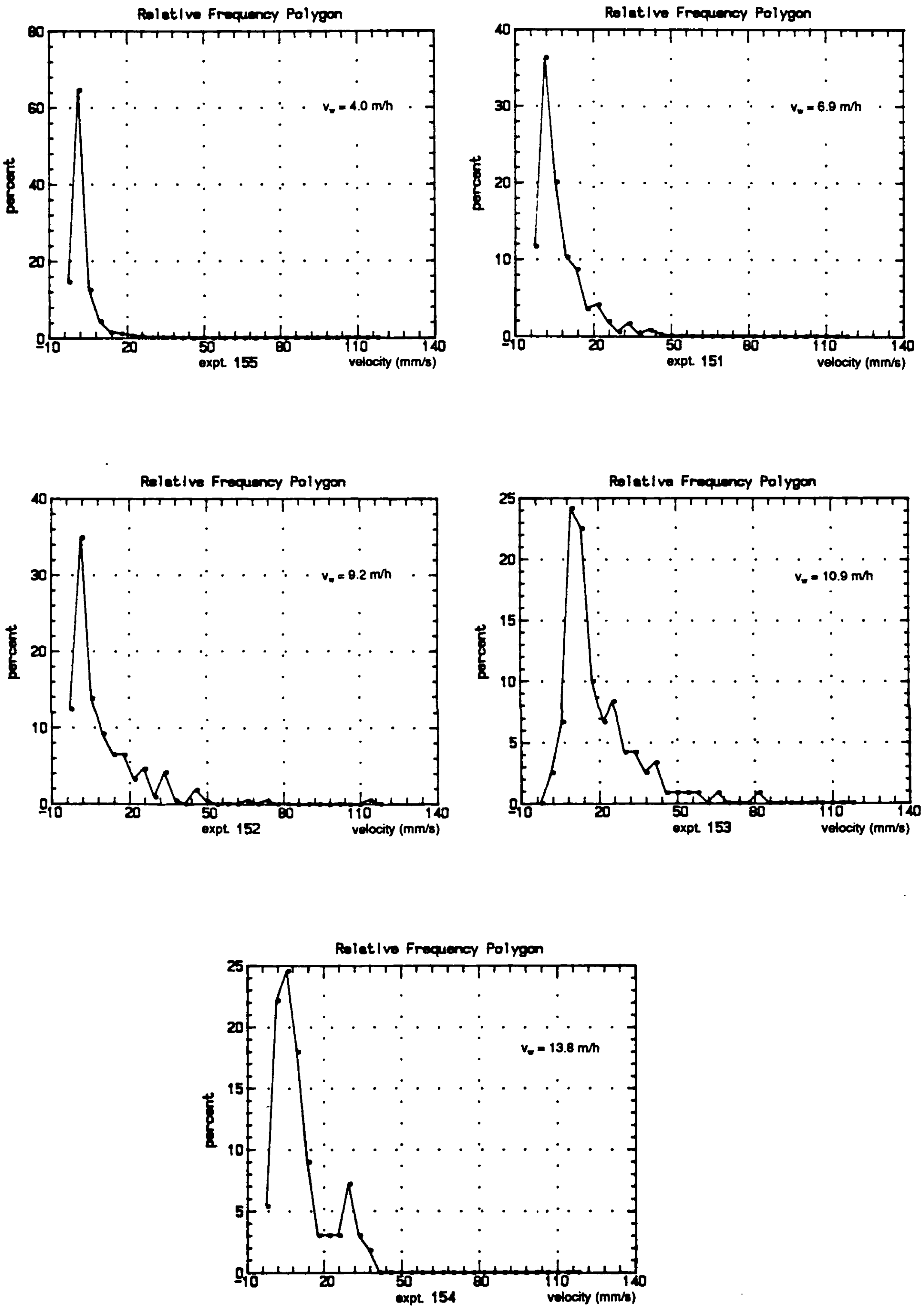


Fig. 6.4. Grain velocity distributions for air + water backwash for different water rates (v_w); air rate, v_a = 73.2 m/h. Bin size = 4.

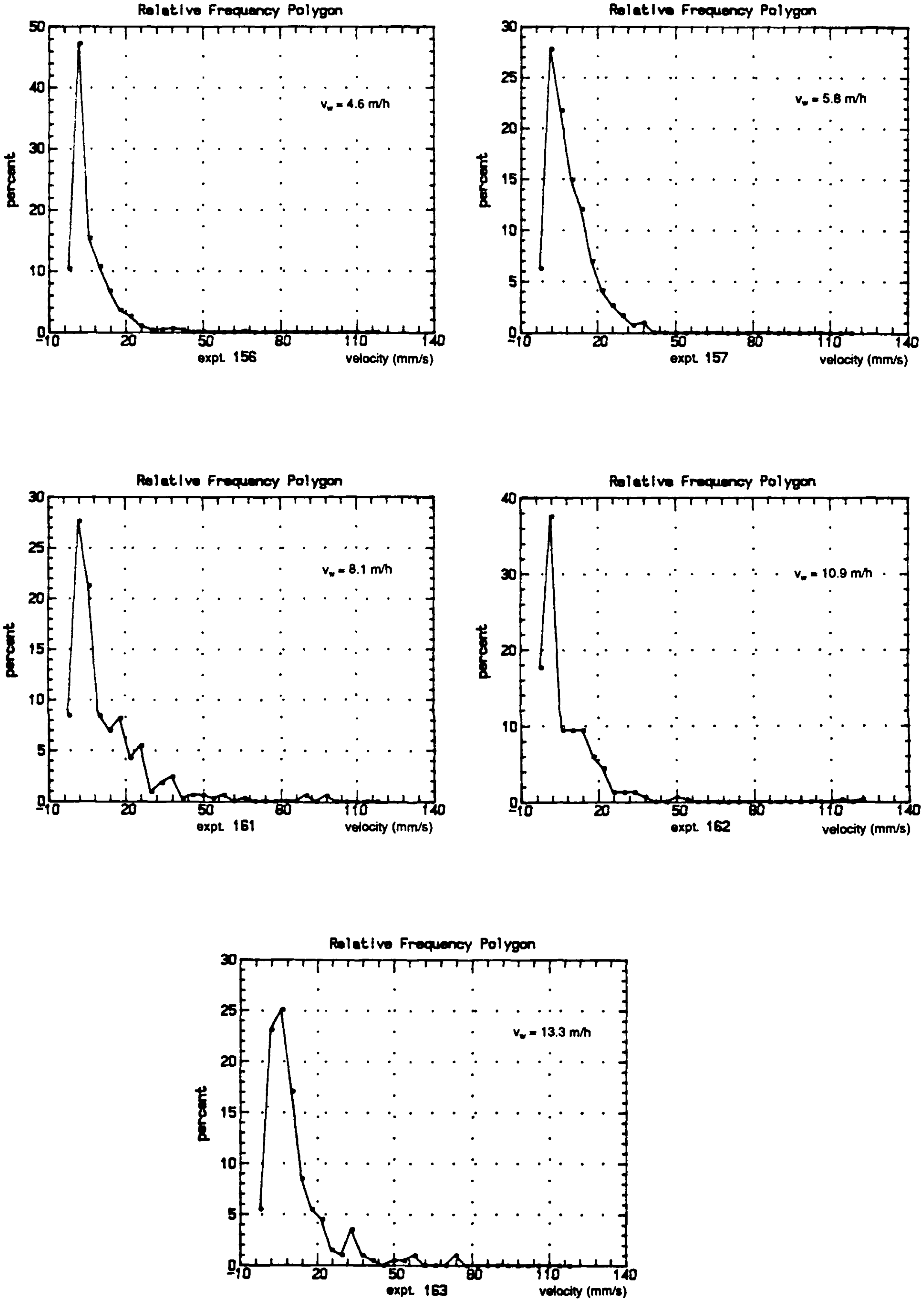


Fig. 6.5 Grain velocity distributions for air + water backwash for different water rates (v_w); air rate, $v_a = 91.2$ m/h. Bin size = 4.

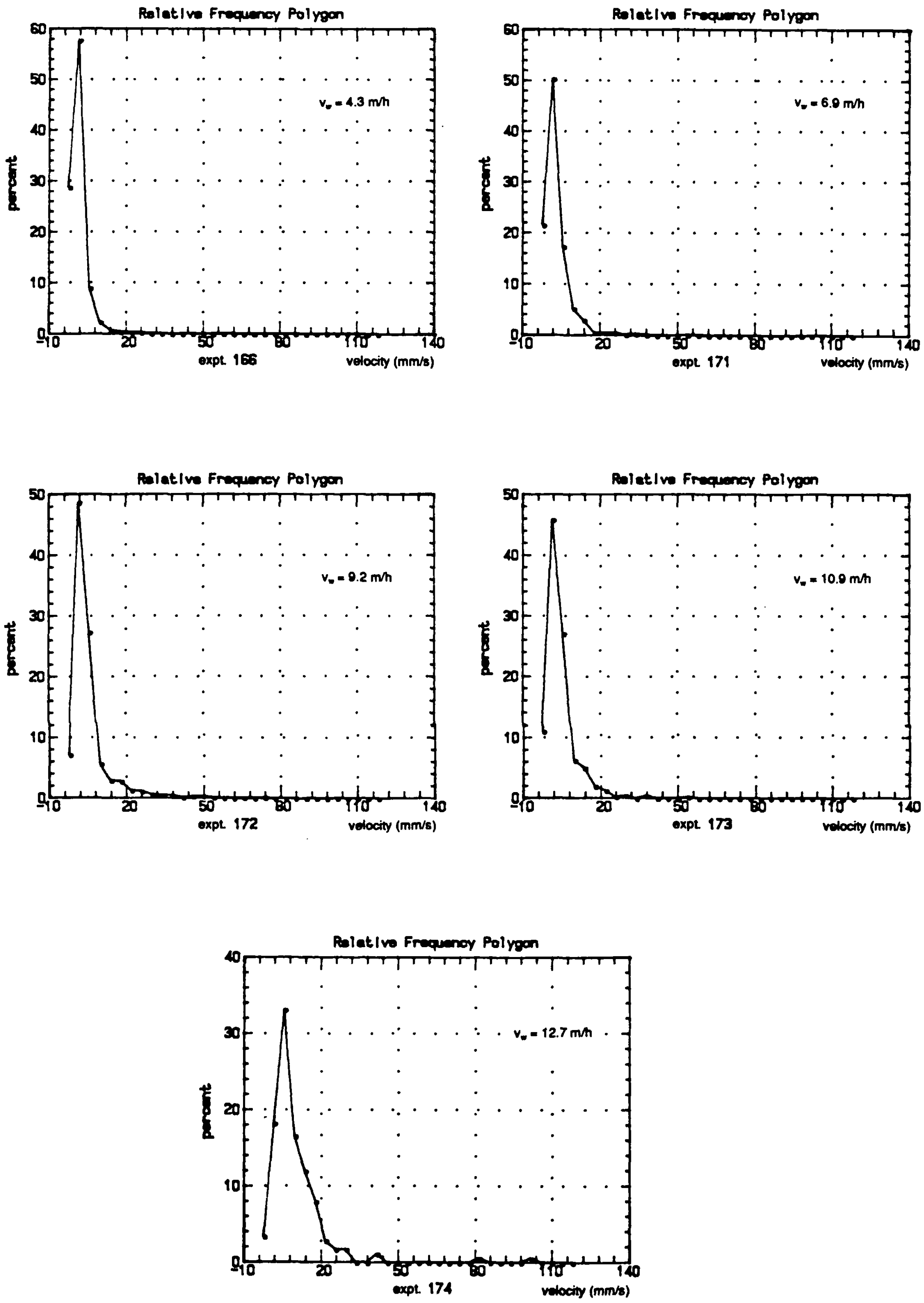
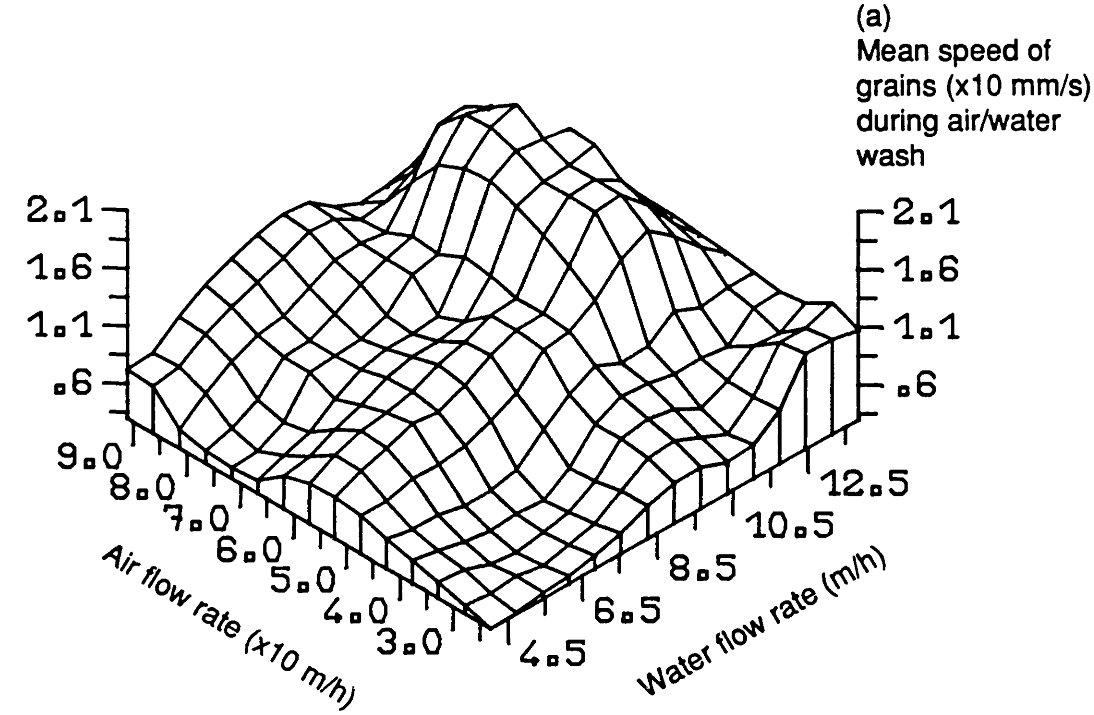


Fig. 6.6 Grain velocity distributions for air + water backwash for different water rates (v_w); air rate, $v_a = 23.0$ m/h. Bin size = 4.



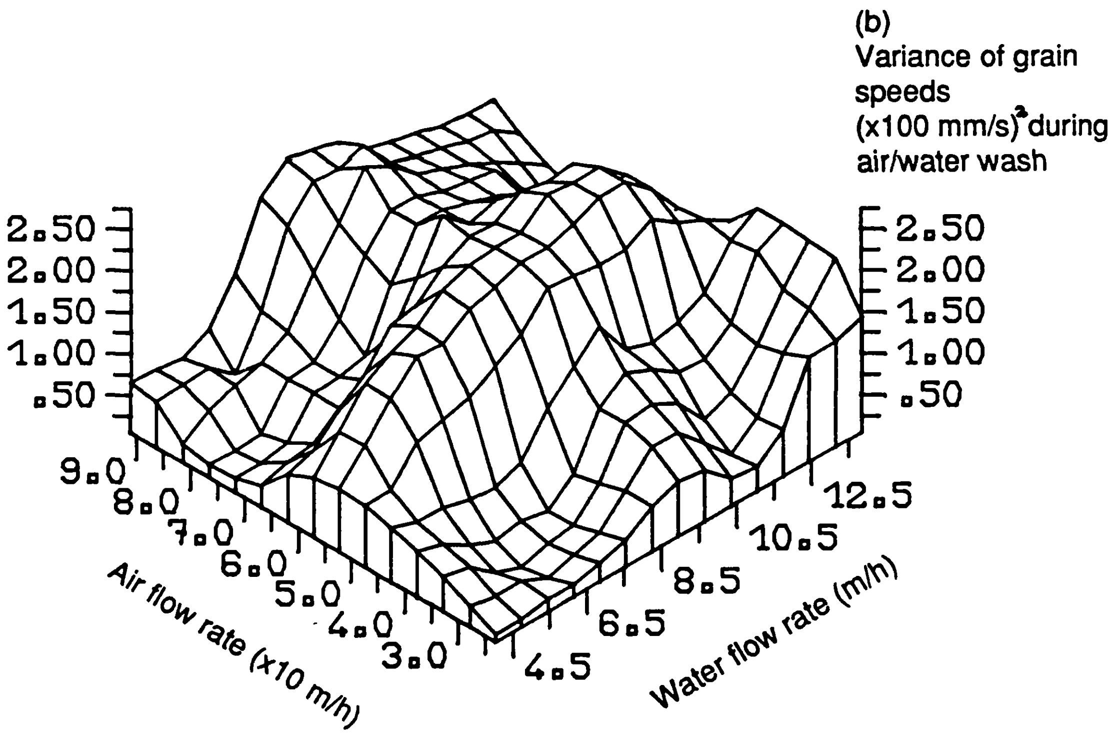


Fig. 6.7. Surface plots of velocity data for combined air and water wash.

7 DISCUSSION OF RESULTS

7.1 Effect of Borescope Insertion Sleeves on Bed Behaviour

It has been observed that the borescope sleeves disrupt the flow patterns in a fluidised bed causing local increases in fluid, and hence grain velocities along the sides of the sleeve. The front end of the sleeve, through which viewing takes place, appears to have little effect on the flow. This is because the face is planar and parallel to the general flow direction. It has been observed that grains viewed through the borescope exhibit more upward than downward motion; in a steady state fluidised bed they should be equal as no nett movement takes place. This may be an effect of the borescope sleeve but more likely is due to the borescopes' position towards the centre of the filter column where jetting can occur. Circulation patterns are set up and when viewed through the column walls show a tendency towards downward motion at the column wall. It is likely that this uneven behaviour occurs in real filter beds as washwater emerges from discrete nozzles. In order to obtain a more complete picture of bed behaviour, i.e. in regions dominated by downward motion, observations should be made at different borescope penetration distances. This could be included in any future research programme.

The projected area of the sleeve in the bed is 330 mm^2 (11mm o.d. x 30 mm penetration distance) and the column area is 10387mm^2, therefore the sleeve occupies 3% of the area of flow at that depth.

It can be concluded that the effect of the borescope insertion sleeves is minimal, especially when compared with viewing through the column wall, particularly in the direction of observation. The borescope and HSV images give an accurate representation of grain behaviour at that depth and penetration distance in the bed. The only way the real situation could be reproduced, without causing flow perturbations due to column geometry, would be to use a model filter with a plan area ~ 1 m^2. This would not be practical in the laboratory and it would not be possible to obtain the detailed visual information described in this thesis. Therefore, for the purpose of this study the model filter column is most suitable.

7.2 Water Only Wash and Fluid Shear Cleaning

The widely held view that collisions between the grains during fluidisation are responsible for the dislodgement of deposits has been proven wrong. Whether, or not, the grains collide is still unclear but this research has shown that it is fluid shear that is responsible for detaching the majority of deposits.

There is little doubt about the presence of shear forces at the sand grain surfaces; they account for all, or most, of the drag forces opposing settling of the grains during fluidisation. Also, it has been argued (Amirtharajah, 1978) that during fluidisation the grains may not actually collide, but only approach extremely closely, due to the increased resistance of the water film as it thins. Two grains approaching one another have to displace the water between them which flows away from the centre of the diminishing gap, creating a high laminar shear stress. This will be discussed in more detail in section 7.2.2.

When the bed is in a subfluidised state the grains are in contact, and as fluidisation commences there will be abrasion between grains as they begin to move and the bed expands. This transition from a packed to a fluidised bed results in intermittent movement of the sand grains whilst still in contact, in the form of rotations and translations resulting in abrasion between grains. Further increases in flowrate intensifies these movements, until the grains are lifted by the water drag into a fluidised mode.

The behaviour of the subfluidised and fluidised bed will be described separately below.

7.2.1 Subfluidised bed

Deposits were observed to detach with the initial reversal of flow at the beginning of backwash; this is solely a result of fluid shear forces as there is no grain movement at this stage. A considerable amount (up to 80 %) of deposits are detached by fluid shear alone in a static bed.

Residual deposits undisturbed by the upflow appeared to lie in sheltered areas of the pores; presumably where the water was virtually stagnant with extremely small shear stresses. However, when the grains moved, even with small relative motion, these sheltered areas became exposed to the flow with consequent shear. As the flow rate increases, the initial grain movement followed by bed expansion appear to expose new faces of the sand grains to the fluid flow, and consequent shear stresses, which carry away the remaining particles.

The shear forces must overcome adhesive forces within the floc and between the floc and the sand grain surface. The kaolin clay is probably destabilised by the calcium ions in the London tapwater (~80 mg/l as Ca^{2+}). Electrostatic forces are thought to be negligible in the adhesions of clay to sand, and clay to clay, particularly as both clay and sand have small negative surface potentials, and the electrical double layer thickness in London tapwater is only 4 nm (Ives and Fitzpatrick, 1989). Therefore the shear forces are probably breaking Van der Waals' bonds, established on roughness contact points on the clays and sand surfaces.

Flocculated clay may have provided a more adhesive floc but experiments showed that kaolin clay flocculated with alum and polymer is as easily sheared as kaolin clay alone. The flocculated clay structures appear more open with relatively large water spaces within the floc. This larger surface area may counteract any increase in adhesive strength as it provides a larger area on which shear forces may act. It may also lead to greater torques arising from greater penetration into the flow velocity gradient.

The mean shear stress in a clogged bed subject to subfluidised flow of 11 m/h (3×10^{-3} m/s =~50% v_{mf}) was calculated by Ives and Fitzpatrick (1989) to be 0.27 Nm^{-2}. The porosity of a clogged bed was assumed to be 0.3 and the shear stress was obtained from the power/fluid volume.

This was a gross estimates with no real definition of stress close to the deposit boundary, where it is higher due to a steeper velocity gradient. An alternative estimate was made from average interstitial flow velocity, and estimation of local pore dimensions and the assumption of a paraboloid velocity distribution (Poiseuille flow).

For a paraboloid velocity distribution $v_i(\max) = 2v_i(\text{mean})$

Mean interstitial velocity $v_i(\text{mean}) = Q/A\varepsilon$ ms^{-1}

At the boundary, velocity gradient $\frac{dv_i}{dr}$

is a maximum and v_i=0.

$$\frac{dv_i}{dr} = \frac{4v_i(\max)}{d} \qquad s^{-1}$$

$$= 4.\frac{2Q}{A\varepsilon d} \qquad s^{-1}$$

Maximum shear stress

$$\tau(\max) = \mu\frac{dv_i}{dr}(\max) = \frac{8\mu Q}{A\varepsilon d} \qquad N\,m^{-2}$$

From experimental data Q/A = 3×10^{-3} ms^{-1} (11 m/h)

porosity ε = 0.3 (estimated for a clogged bed)

pore "diameter" d = 0.20 mm = 0.20×10^{-3} m

absolute viscosity μ = 10^{-3} N s m^{-2} (20°C)

From which $\tau(max)$ = 0.40 N m^{-2}

Also from the paraboloid velocity distribution

$\tau(mean)$ = 2/3 x $\tau(max)$

$\tau(mean)$ = 0.27 N m^{-2}

Both estimates of mean shear stress, and the further estimate of maximum shear stress are based on assumptions which do not take into account local pore geometry, but they indicate order-of-magnitude values.

The value for shear stress obtained by Ives and Fitzpatrick (1989) for subfluidised washing assumes a porosity, ε, of 0.3. It is possible that in the top few cm of the bed ε = 0.15, which would double the shear stress value to τ = 0.54 Nm^{-2}, since $\tau \propto 1/\varepsilon$. But, this value for shear stress is an average value, calculated on an assumption of a paraboloid velocity distribution within the pores. It is probable that it is the maximum values of τ which are responsible for detaching deposits, which in this case would be 0.81 Nm^{-2}. These calculations are for a flow rate of 11 m/h (~ 50 % v_{mf}) which is around the maximum flow rate for which the grains are still stationary. Beyond this the grains start to move, particularly as the deposits break up and leave the grain surfaces, affecting the velocity distributions.

7.2.2 Fluidised bed

As upflow velocity was increased, the grains exhibited more violent motion, and their rotations and translations, when in contact, provided mild grinding action. The rubbing together of grains, which are moving but not fully fluidised, is the basis of sand filter cleaning practised by one filter manufacturer. The operating requirement is that all the filter grains should be mobile, but not significantly expanded into a fully fluidised state. In this case, the mobility of the grains will ensure exposure of all faces to the shearing effect of the flow and encourage detachment and release of deposits. Grain collisions and abrasion may play a part in enhancing detachment but it is clear that these do not dominate the process, otherwise there would be a tendency for deposits to remain trapped in crevices on grain surfaces, where there was no possibility of collisional contact. Deposits in crevices would be removed by fluid shear as grains approach and force the fluid to flow in crevices, flushing out the deposits.

It is known that the abrasive action is not sufficient to wear away surfaces of the quartz sand grains in the operational life of a water filter (e.g. 10 years). The presence of water as a lubricant has some ameliorating effect, in the form of damping collisional energies, but also the water induced forces on a grain are relatively weak and are theoretically less than or equal to the grain weight in water. Such a force is only about 0.2 mN for a 0.6 mm sand grain in water. If the grain is accelerated, then greater forces are involved. This happens when the fluid velocity distribution is non uniform as observed on the video recordings.

In full fluidisation all the grains are supported by upward fluid drag and the bed is in an overall steady state as predicted from theory. Locally, apparently random motions of grains or clusters of grains are observed inside the bed. These have intermittent periods of rest and vigorous motion, i.e. on a grain scale the fluidised bed is not in a steady state. On a macroscopic scale there is equilibrium, where the grain weight in the fluid is balanced by the upward drag forces, but locally grains are moving upwards and downwards implying that the drag force exceeds or is less than the grain weight, respectively.

Grains with upward velocities may appear to move faster, perhaps as they are moving with the flow, in regions where fluid velocities are higher. Downward moving grains move against the flow, which must be less than the mean v_l as the drag is insufficient to overcome settling. The mean flow is constant ($= v_w$) and the overall flux of grains is also constant and equal to zero, i.e the number of grains moving up equals the number moving down. Grains moving upwards may have higher velocities but have lower number densities, whilst those moving down have lower velocities and higher number densities. The more dense packing would tend to decrease the interstitial velocities, as well as resulting from a decrease in flow. When the grains move upwards they expand as a result of the fluid drag, eventually the state becomes unstable. These patterns repeat in space and time throughout the bed.

Collisions are more likely to occur when clusters of grains are moving downwards, as locally the grains are not fluidised. Sudden changes in direction of grains may cause collisions. The question of whether the grains actually collide when fluidised or whether they just approach extremely closely will be discussed in more detail.

Amirtharajah (1978) argued that as the separation between grains approaches zero then the drag force tends to ∞, i.e. as the fluid film thins more viscous forces arise from the increased velocity gradient, reducing the energy of approaching grains, and becoming more resistant to displacement. One possibility is that the fluid drag reduces the energy of the grains sufficiently that they come to rest as they make contact. Collisions must exist of lower and higher energy where grains do not collide or collide with some force, respectively. If the grains never penetrate the fluid film then it may cause them to rebound and behave in a similar way to if a collision had taken place; this would depend on fluid behaviour under such conditions which is not known at present and future work could include a calculation of these fluid drag forces.

For laminar flow the shear stress on the grain surface increases linearly with flow rate but this assumes grains to be fixed. Once the bed has expanded and fluidised then turbulence can develop associated with the moving grains. The average shear stress on grains increases until it reaches a maximum value, dictated by the conditions of turbulence. Amirtharajah (1978) predicted that this occurs at around 40 - 50 % expansion (porosity of 0.65 - 0.7). The theory assumes that an average shear stress exists throughout the bed; observations in the present study indicate this is untrue. However, the average shear stresses in a fully fluidised bed are greater than in a just fluidised bed because of the increased drag required to maintain the grains in a fluidised state. But, the range of grain velocities and hence the maximum shear stresses on grain surfaces may not be significantly higher, thereby not improving deposit detachment. The grains exhibit highly fluctuating velocities which will have associated fluctuations in shear stress. Since theoretical calculations have suggested the existence of turbulence then it is possible that turbulent forces may detach deposits (as discussed by Amirtharajah and Giourgas, 1981). However, observation from the video have shown that most of the deposits have detached, due to fluid shear forces, by the time the bed has fully expanded and so the contribution of turbulent forces to cleaning will be negligible. ✓

It should be noted that the shear stresses are related to the fluid viscosity and that fluctuations in temperature will affect bed behaviour: an increase in temperature leads to a reduction in viscosity and hence shear stresses and bed expansion.

In chapter 5 it was noted that the clogged bed behaves differently from the clean bed due to the reduction in porosity, particularly towards the surface of the bed, by deposits. Addicks (1990) noted that deposits on grains affect the fluidisation behaviour, due to grain size changes. In the experiments described in this thesis, kaolin deposits did not adhere to grains for long enough to affect fluidisation behaviour subsequent to the initial effects. In the case of biofilms, however, there may be an effect.

Experiments conducted using water wash only have shown that a considerable amount of kaolin deposits can be removed by fluid shear alone (see chapter 5 and video), since when the bed is fluidised collisions are not significant, and, in the subfluidised state, where no grain movement takes place, large amounts of deposit are removed. When the bed is in a partially fluidised state abrasion between grains may contribute to detachment while the bed is expanding. The bed must pass through this phase as flow is increasing for fluidised washing.

It was not possible with the experimental set-up to test Amirtharajah's (1978) prediction of maximum efficiency at 40 - 50 % expansion. It is thought that no increase in removal efficiency would have been observed, as the writer's results indicate that a plateau in efficiency had been reached.

These observations of fluid shear detachment of deposits cast doubt on Huang and Basagoiti's (1989) model which assumed that no detachment takes place until the bed is fluidised. This is incorrect as a significant amount of solids dislodgment takes place as soon as flow reversal starts. The authors obtained the desired bed expansion within 5 seconds of introducing the backwash water; this would be sufficient time for a significant proportion of deposits to be detached by the subfluidisation flow and continue to be detached and flushed out as the bed expands. Later, in their results section the same authors discussed backwashing requirements and bed cleaning efficiency. They stated that efficiency was highest when the bed was expanded by 70 - 90 %. This is not in agreement with Amirtharajah's (1978) prediction of maximum shear stress at 40 - 50 % expansion for graded sand.

This work has shown that the resistance of deposits, and deposit attachments, to shear stress is a fundamental property governing detachment processes. This will be affected by the nature and properties of the deposits and further work with more adhesive deposits, e.g. biological material, is required in order to ensure that these can be detached by fluid shear forces. However, there were no marked differences when kaolin flocculated with alum and polymer was used as the clogging suspension, i.e. no build up of deposits on grain surfaces was observed.

7.3 Cleaning Mechanisms and Bed Behaviour during Air Scour

The introduction of air into the sand bed causes grain agitation even when there is no water flow, but the distribution of air tends to be restricted to preferred routes. When a low water flow is applied, in conjunction with the air flow, the grains can move more freely due to a reduction in the effective stresses between them. At collapse-pulsing combinations there is maximum agitation and circulation of the bed. As the water rate is increased beyond about 50 % v_{mf} grains can move more freely and the air passes through the bed with less disturbance.

During combined air and water wash at collapse-pulsing the sand bed pulsates giving local grain velocities as high as those observed in a fully fluidised bed (see section 6.2), but this is achieved with much lower water rates (~ 20 - 45 % v_{mf}). These rapidly changing velocities would give rise to high fluid shear stresses on the grains and attached deposits, in addition to the stresses from abrasion and grain collisions when the sand collapses into the wake of passing air bubbles. Additionally, there may be shear stresses on grain surfaces due to surface tension of a moving water film at the air/water interface of a passing air bubble, which can be observed on the video recordings. The surface tension forces present in the air/water interface exert forces on the grains which may be sufficient to cause local contraction of the bed and detachment of deposits.

Overall bed contraction results from the agitation produced by passing air bubbles, causing grain rearrangement and bed consolidation. This was noted by Lee and Al-Dabbagh (1978) who observed bed contraction to 92 % of the original height when the bed was in a jumping regime during combined gas and liquid flow. This jumping regime may correspond to what is described as collapse-pulsing. Addicks' (1989) observation of maximum contraction (of 5 - 10 %) for v_w = 60 % v_{mf} is probably after the onset of collapse-pulsing, if the Amirtharajah (1984) equation holds. A decrease in efficiency was observed in the present writer's experiments at these flow rate combinations. Additionally, the writer's observations indicated that maximum contraction occurs for 0 - 25 % v_{mf}.

Regan and Amirtharajah (1984) get lower % v_{mf} to achieve collapse-pulsing with larger media, although Hewitt (1984) states that the collapse-pulsing equation is independent of size. Therefore if the equation holds for Addicks' media, 60 % v_{mf} is above the v_w required for collapse-pulsing. Roberts (1986) stated that his equation predicting three phase fluidisation (which he believes corresponds to collapse-pulsing) of

$$v_l = \frac{a}{v_g^{0.47}}$$

holds for all particle sizes (a is a constant).

Addicks' (1990) graph of bed behaviour (fig. 3 in his paper) indicated that for v_w = 0 at a constant v_g there is no bed contraction. It has been observed by the writer (chapter 5) that there is contraction, possibly maximum, of the bed at these rates when 0.5 - 1.0 mm sand is used. However, it has been observed by others (e.g. Peterson et al., 1987) that bed contraction occurs for particles of < 3 mm diameter when air is introduced into a liquid *fluidised* bed so it is possible that maximum contraction occurs at different flow rate combinations for different sized media. As water flow rate increases the bed slowly expands until it is fluidised. Addicks concluded that the maximum bed contraction causes maximum abrasion between grains, which is probably true as it would increase the normal or frictional stresses, but the writer disagrees with the idea that this is a maximum around 60 % v_{mf} as water flow is sufficient to reduce stresses. There may be a trade-off due to the increased bed circulation and collapse-pulsing is the optimum at ~ 40 % v_{mf}, as predicted by Amirtharajah and co-workers.

Amirtharajah (1984) argued that it is the collapse of grains in the bubble wake with associated abrasion that is the main cleaning mechanism. Addicks (1989) suggested that it is the action of bed contraction. It is probable that both of these mechanisms have an effect on deposit detachment since they result in grain movement and abrasion. At the start of a combined air and water wash both occur simultaneously, so it would be difficult to distinguish which has greater effect.

It may be possible to obtain a link between collapse-pulsing and three phase fluidisation, where all solids are supported by the upflowing fluids, but the writer was unable to find a way of measuring this experimentally, due to the nature of manometers used (air in the system disrupts readings). Three phase fluidisation occurs when the weight of the grains is supported by the combined effect of the two upflowing fluids.

From video observations it is clear that fluid shear is the dominant detachment mechanism during collapse-pulsing. Simultaneous air and water wash may maximise detachment because it maximises fluid shear and grain collisions when in the collapse-pulsing state. It is important to fluidise the bed with water after air has been used in order to re-stratify mixed media and remove any air and loosened deposits trapped within the bed. Since fluidisation is required for this purpose, more water may be required for the same cleaning efficiency as may be achieved with low expansion fluidised water wash which will not mix media or trap air. The total washwater volume can be minimised by finding the minimum duration and flow rates required for this flushing process.

The data in section 5.3 indicates that an air water wash for 2.5 - 3 min at collapse-pulsing would be sufficient to dislodge all deposits, followed by a fluidising water wash between v_{mf} and $2v_{mf}$, for about 3 min, to flush out all loosened deposits and trapped air. The writer's observations support those of Addicks (1989) in that most deposits are detached during the first 1 - 2 min. of washing. He suggested a repetitive cycle would be more efficient, because of his suggestion that contraction causes cleaning, which ties in with the frequent observations which indicated that stopping and restarting the wash led to removal of more deposits.

The work of Moll (1990) is discussed in the light of the present writers findings. Moll described a series of experiments with a model filter looking at the effectiveness of different water wash rates and the use of air scour. He found that air scour followed by combined air and water wash did not improve subsequent filter performance (initial head loss and filter run time). The writer notes that in many cases the water wash was well below v_{mf} and would probably have been insufficient to flush out all deposits and trapped air, resulting in the increased head loss indicated by his data. Where air plus water was used the water rate was insufficient to cause collapse-pulsing. All runs were finished off with a water wash and it is noticeable that when this wash was sufficient for fluidisation the head loss at the beginning of subsequent filter runs remains consistently low and the writer believes should approach that of a clean bed. The curves drawn through the author's data for head loss and run time are an incorrect interpretation of the data as they should be asymptotic towards the values for starting with a 'clean' bed. The author noted that his data indicates the much quoted optimum at 25 % expansion but the writer believes there is insufficient data from which to draw this conclusion.

Some experiences of backwash operations with air scour at treatment works reveal a gap in the understanding of the mechanisms involved as described below. In a review of backwashing procedures Watson (1987) noted that backwashing procedures were not modified at Bedford and Grafham treatment works when GAC was installed in place of the existing anthracite/sand, apart from increasing weir heights to reduce media losses (Chadwick and Leech, 1988). As a result the backwashing may not be operating at optimum efficiency due to the new properties of the media. At Pitsford the duration of a water only wash was increased but the writer believes that greater efficiency could be achieved by finding the optimum flow rate or introducing air scour, if media losses could be overcome. Filter beds at Wing receive 5 min of air scour followed by 2 min delay then a 6 min water wash with no expansion. The writer believes that there could be 2 potential problems: (i) the delay between air scour, which detaches deposits, and water wash to flush out the deposits may lead to some deposit re-adhesion, and (ii) a water wash with zero expansion could be insufficient to remove all deposits and air trapped in pores thereby reducing subsequent filter run times. Other works in the Anglian Water region use various combinations of air and water as well as a cross wash of water. Watson's review provides an indication of the lack of knowledge of filter backwashing mechanisms and in particular what rates cause maximum cleaning efficiency. It appears that flow rates and durations are somewhat arbitrarily chosen, particularly following a change in filter media.

Bablon *et al.* (1988) when considering conversion of sand filters to dual media sand-GAC filters stressed the importance of pilot tests in determining backwashing procedures; they particularly noted the effects of water temperature on bed behaviour during backwashing. If air scour is used then mixing of the dual media will occur and a water wash at > v_{mf} will be required for the restratification necessary for good filter performance. They do not recommend combined air and water wash as this causes media losses unless the washwater weir height is increased on conversion to a dual media filter. The washing procedure recommended by Bablon *et al.* involves 4 stages: (i) water level drained to top of GAC, (ii) air scour at 30 m/h for 5 min., (iii) water wash only at 38 m/h until it reaches the weir, to restratify the bed and flush out air, and (iv) rinsing at 25 m/h for 20 min.. The writer believes that these flow rates should be determined experimentally for each individual case and that 5 min. of air scour may be too long; it may be better to utilise a combined air/water wash at collapse-pulsing for a short duration (e.g. until water reaches overflow weir) and then commence the high rate water wash. Additionally, 20 min. seems rather long for flushing out loosened deposits, assuming the bed is fluidised, which it was in the authors' experiments.

It is clear that the mechanisms of deposit detachment during air scour were not understood. The present work shows that fluid shear is the major detachment mechanism during combined air/water wash of a bed clogged with kaolin, or the more adhesive kaolin flocculated with alum and polymer. Collapse-pulsing provided a high efficiency washing process by maximising fluid shear forces and grain abrasion to enhance cleaning.

7.4 Grain Velocities

For water only wash velocity measurements indicate an increase in the range and mean of velocities as flow rate increases. For a fluidised bed the velocity distributions show a bimodal tendency which may be due to the circulation patterns set up giving rise to spatial and temporal phases of high and relatively low grain activity. The velocities of the grains will affect the shear stress on their surfaces as well as the degree of turbulence in a fully fluidised bed.

The velocity distributions exhibit skewness and have a characteristic shape similar to those described by Haff and Werner (1987) who obtained velocity distributions from a computer simulation of inelastic spheres. The mode, or peak value, on their distributions increases with the energy input. This corresponds to the increase in modal value observed in the writer's results for increases in fluid flow rate; which is the energy source for the grains. The range, and consequent maxima, of velocities increase with increasing water rate. This maximum is what ultimately controls detachment of the more adhesive deposits. The maximum velocity observed was about 80 mm/s for a fluidised bed.

The observation of more upward than downward grain motion in the fluidised bed may be due to the fact that although velocities are higher going upwards, the grain concentration is less as discussed in section 7.2.2. The velocity distributions do not take direction into account as they indicate the magnitude only which is related to the fluid drag force.

If an average of the results for experiments 111 and 112 are taken we get a mean grain velocity

$$v_s(\text{mean}) = 8.3 \text{ mm/s}$$

and the water approach velocity

$$v_w = 26 \text{ m/h} = 7.2 \text{ mm/s}.$$

For 2.4 % expansion the porosity of the bed, $\varepsilon_e = 0.44$.

Therefore, the mean interstitial water velocity, $v_i(\text{mean}) = v_w/\varepsilon = 16.4$ mm/s.

i.e. the mean grain velocity is about half the mean interstitial fluid velocity. The maximum grain velocity in these two experiments was 33.3 mm/s, approximately double v_i(mean), i.e. it is similar to v_i(max), which equals $2v_i(\text{mean}) = 32$ mm/s. It should be noted that these calculations are based on a paraboloid velocity distribution within pores and uniform flow throughout the bed, locally there must be variations in the flow giving a range of pore velocities. Assuming the bed is in an unsteady state, it can be argued that the measured maximum grain velocity must be a result of a local maximum fluid velocity which transfers energy to the grains. Since energy would be lost in this process, in drag forces arising from the density difference and consequent inertia of grains, then the maximum grain velocity must always be less than the maximum fluid velocity. Similarly, the mean interstitial fluid velocity will be greater than the mean grain velocity. Future work could build on the relationship between fluid and grain velocity distributions and relate this to the energy dissipated in drag forces and consequently used in cleaning.

For air scour, it is noticeable that similar grain velocities can be achieved with significantly less water input, i.e. similar shear stresses are obtained. The maximum velocity observed for collapse-pulsing combinations of air and water flow was around 90 mm/s which is higher than for a fluidised bed. This implies that the shear stress acting on the grain surface must also be higher, particularly as velocity gradients are steeper as porosity is less. It can also be observed that in fig. 6.6 the velocities are markedly lower, supporting Amirtharajah's (1984) collapse-pulsing equation which indicates that this air flow rate is too low to achieve the desired bed behaviour.

The velocity measurements provide an indication of the energy of the grains under different washing regimes and, as velocity is closely related to the shear stress on the grain surface, provide an indication of washing efficiency.

7.5 Summary of Washing Procedures and Recommendations

The results of the different backwashing experiments are summarised below. Note that this is based on experiments with kaolin and flocculated kaolin.

The fluidising water wash was sufficient for removal of deposits. The previously predicted optimum expansion (Amirtharajah, 1978) of 40 - 50 % does not appear to be necessary as the fluid shear at very low expansions appears to be sufficient for removal of deposits. Some expansion is necessary in order to ensure all faces of the grains are exposed to the flow and to enhance flushing out of loosened deposits. Tests should be made using more adhesive deposits to ensure that the fluid shear forces are adequate.

If air scour is employed then collapse-pulsing combinations of air and water flow are recommended. This ensures maximum fluid shear forces and abrasion for removal of the more adhesive deposits. A duration of 2 to 3 min is recommended followed by a fluidising water wash at around 200 % v/v_{mf} to flush out the remaining loosened deposits and trapped air. The actual rate and duration of this final wash should be found by a series of tests.

Water rate	Air rate	Duration (min.)	Efficiency (%)	Grain velocity	Comments
subfluidised ≤ 70 % v/v_{mf}	0	≤ 20	up to 90	v_s(mean) = 0 to 0.15 mm/s v_s(max) = 0 to 20 mm/s	Deposits detached by fluid shear forces and possibly some abrasion at higher wash rates. Higher rates require shorter wash to achieve same removal, i.e. volume of washwater constant.
fluidised wash	0	≤ 7	≥ 90	v_s(mean) = 8 to 25 mm/s v_s(max) = 20 to 80 mm/s	Deposits detached by fluid shear forces. Expansion exposed new faces of grains to flow and flushes out deposits. Some abrasion as bed expands and some collisions but only minor contribution to detachment.
40 - 50 % v/v_{mf}	35 - 90 m/h	5	≥ 90	v_s(mean) = 7 to 20 mm/s v_s(max) = 100 to 150 mm/s	Fluid shear dominant mechanism but abrasion increased by collapse-pulsing behaviour of bed. Good bed circulation exposes new faces of grains to flow and releases some deposits.
followed by 200 % v/v_{mf}		1 - 3	~ few %		Final flushing out of loosened deposits and trapped air.

Table 7.1. Summary of results for different backwashing procedures.

8 CONCLUSIONS

1. Using the borescope and high speed video set up it is possible to observe locally the filter backwashing process when washed with water only and when air scour is introduced.

2. Collected and analysed backwash water gives information about the efficiency of the wash in terms of quantity of deposits removed particularly for the water only backwash experiments.

3. The turbidity data provides valuable parameters for measuring backwashing efficiency that are more reliable than the mass balance results.

4. It has been observed that the clogged bed behaves differently from a clean bed during water backwash. Grain movement occurs in the top layer of a clogged bed for flows as low as 8m/h, whereas in the clean bed a flow rate of 17 m/h is required. The top layer of the clogged bed expands and then resettles due to higher velocities in the restricted pore space.

5. The experiments conducted using water wash only have shown that a considerable amount of kaolin and flocculated kaolin deposits can be detached by fluid shear. For higher subfluidisation wash rates abrasion between mobile grains may enhance the process. At fluidising rates, movement of the grains serves to expose new deposits to the shearing effect of fluid flow and allow flushing out of detached deposits. When the bed is fully fluidised collisions are negligible. Abrasion between grains may contribute to detachment while the bed is expanding as flow is increasing for fluidised washing. This evidence suggests that for these experiments the dominant detachment mechanism is fluid shear. Consequently, the resistance of deposits, and deposit attachments, to shear stress seems to be a fundamental property governing the detachment process.

6. When the bed is fully fluidised, results for a kaolin clogged bed show that there is no significant increase in removal efficiency for expansions > 15% (40 m/h upflow).

7. For combined air and water wash, followed by bed fluidisation with water only, optimum cleaning occurs at flow rates satisfying the collapse-pulsing condition predicted by Amirtharajah (1984). Removal is principally by fluid shear enhanced by abrasion between grains during collapse-pulsing. Additionally, detached flocs of deposits may be broken up by the violent motion within the bed making them

easier to flush out. Subsequent water wash is required to flush out the detached deposits from within the bed. The total washwater volume can be minimised by finding the minimum duration and flow rates required for this flushing process.

8. It is important to fluidise the bed with water after air has been used in order to re-stratify mixed media and remove any air trapped within the sand.

9. The data indicates that an air water wash for 2.5 - 3 min at collapse-pulsing would be sufficient to dislodge all deposits, followed by a fluidising water wash between v_{mf} and $2v_{mf}$ to flush out all loosened deposits and trapped air.

10. Experiments using kaolin flocculated with alum and polymer show no significant difference in floc adhesion as they are readily detached by fluid shear forces.

11. Several publications have arisen from this research and can be seen in Appendix IV.

12. Further work is required as detailed below:

theoretical developments could include:

(i) more accurate and detailed predictions of shear stresses on grain surfaces for different bed conditions,

(ii) relating collapse-pulsing theory to that of three phase fluidisation,

(iii) calculation of the shear stresses from thinning fluid films and moving air/water interfaces on grain surfaces,

(iv) analysis of the fluid and grain velocity distributions and relate them to energy dissipated in drag forces and hence cleaning.

practical developments could include:

(i) detailed evaluation of the effect of borescopes on bed and local grain behaviour,

(ii) looking at the behaviour of more adhesive deposits, e.g. biological material, during backwashing,

(iii) evaluation of the effect of media type and size on bed behaviour,

(iv) development of a technique for measuring head loss in the three phase bed,

(v) obtaining grain velocity measurements for the whole bed,

(vi) use of the video analysis equipment to measure other parameters.

9 REFERENCES

Addicks, R. (1989). A contribution to the backwashing of rapid granular media filters. Proceedings of the Filtech Europa Karlsruhe Conf. Sept. 12-14, 1989. Filtration Society, 298-308.

Addicks. R. (1990). Optimal simultaneous backwash of rapid granular media filters with air and water in terms of three-phase fluidisation. Proceedings of the Vth World Filtration Congress, Nice, France. June 1990.

Ahmad, R., Chaudhuri, M. (1989). Characteristics of filter backwash water at the Kanpur water works. Journal of the Indian Water Works Assoc., 20 (4), 293-297.

Amirtharajah, A., Giourgas, A. J. (1981). Theory for particle detachment from sand grains during backwashing of filters. International Symposium on Applications of Fluid Mechanics and Heat Transfer to Energy and Environmental Problems. University of Patras, Patras, Greece.

Amirtharajah, A., Morrison, R. J., Holnbeck, S. R., (1981). The mechanics of air scour during filter backwash. 1981 Annual Conference Proceedings, Part 1, American Water Works Assoc., 209-239.

Amirtharajah, A., Trusler, T. (1982). Studies on the loss of media during air scour. 1982 Annual Conference Proceedings, Part 1, American Water Works Assoc., 387-404.

Amirtharajah, A. (1978). Optimum backwashing of sand filters. A.S.C.E. Journal of Environmental Engineering, 104 (EE5), 917-932.

Amirtharajah, A. (1984). Fundamentals and theory of air scour. A.S.C.E. Journal of Environmental Engineering, 110 (3), 573-590.

Bablon, G. P., Ventresque, C., Ben Aïm, R. (1988). Developing a sand-GAC filter to achieve high-rate biological filtration. Journal of the American Water Works Assoc., 80 (12), 47-53.

Ben Aïm, R., Ventresque, C. (1986). Conditions for backwashing dual media filters. Eau, Industrie, Nuisances, No. 103, 28-30. (In French).

Bhargava, D. S., Ojha, C. S. P. (1989). Theoretical analysis of backwash time in rapid sand filters. Water Research, 23 (5), 581-587.

Braaten, D. A., Paw, U. K. T., Shaw, R. H. (1988). Coherent turbulent structures and particle detachment in boundary layer flows. J. Aerosol Sci., 19 (7), 1183-1186.

Bratby, J. R. (1988). Optimizing manganese removal and washwater recovery at a direct filtration plant in Brazil. Journal of the American Water Works Assoc., 80 (12), 71-81.

Chadwick, B., Leech, J. (1988). GAC for rapid filtration. I.W.E.M. Scientific Section: Symposium on rapid filtration of potable waters, Huntingdon, U.K., 16 February 1988.

Clark, R. G. (1988). Experiences in filtration for iron and manganese removal. I.W.E.M. Scientific Section: Symposium on rapid filtration of potable waters, Huntingdon, U.K., 16 February 1988.

Cleasby, J. L., Fan, K-S. (1981). Predicting fluidisation and expansion of filter media. A.S.C.E Journal of Environmental Engineering, 107 (3), 455-471.

Cleasby, J. L. *et al.* (1977). Backwashing of granular filters. Journal of the American Water Works Association, 69 (2), 115-126.

Clough, G., Ives, K. J., (1986). Deep bed filtration mechanisms observed with fibre optic endoscopes and CCTV. 4th World Filtration Congress. Ostend, Belgium, April 1986.

Currier, R., Heman, M. F. (1987). A non-Markovian model for particle motion in fluidised beds. Chem. Eng. Commun., 56 (1-6), 1987, 203-209.

Dhamarajah, A. H., Cleasby, J. L. (1986). Predicting the expansion behaviour of filter media. Journal of the American Water Works Assoc., 78, 66-76.

Durst, F., Milojavic, D., Schönung, B. (1984). Eulerian and Lagrangian predictions of particulate two-phase flows: a numerical study. Appl. Math. Modelling, Vol. 8, April, 101-115.

Fitzpatrick, C. S. B. (1990). Detachment of deposits by fluid shear during filter backwashing. Proceedings of IAWPRC - IWSA Joint Specialist Conference, Jönköping, Sweden 24-26 April 1990, Water Supply, Vol. 8, 177-183.

Fourie, J., Ives, K. J., (1982). Continuous countercurrent filtration. Proc. Symp. Water Filtration, KVIV Antwerp 1982, 3.7 - 3.18.

Govan, A. H., Hewitt, G. F., Ngan, C. F. (1989). Particle motion in turbulent pipe flow. Int. J. Multiphase Flow, 15 (3), 471-481.

Haff, P. K., Werner, B. T. (1987). The collision interaction of a small number of confined inelastic grains. Particulate and Multiphase Processes; Int. Symp., Hemisphere, Vol. 3, 483-501.

Hakumo, M., Tarumi, Y. (1988). A granular assembly simulation for the seismic liquefaction of sand. Japan Soc. of Civil Engineers, Structural Eng./ Earthquake Eng., 5 (2), 332s-342s.

Hewitt, S. R. Amirtharajah, A. (1984). Air dynamics through filter media during air scour. A.S.C.E Journal of Environmental Engineering, 110 (3), 591-606.

Huang, J. Y. C, Basagoiti, J. (1989). Effect of solids property on rates of solids dislodgment. A.S.C.E. Journal of the Environmental Engineering Division, 115 (1), 3-19.

Ives, K. J., Clough, G., (1985). Optical fibre investigations of filtration processes. 4th IAWPRC Workshop on Instrumentation and Control of Water and Wastewater Treatment and Transport Systems. Houston, Texas, U.S.A., April 1985, Pergamon, Oxford.

Ives, K. J., Fitzpatrick, C. S. B. (1989). Detachment of deposits from sand grains. Colloids and Surfaces, 39, 239-253.

Ives, K. J. (1986). Developments in deep bed filtration. Chemical Engineering; World Congress III, Soc Chem Eng Jpn, 1986, Vol III, 69-72.

Ives, K. J. (1987). Filtration of clay suspensions through sand. Clay Minerals, 22, 49-61.

Jin, G. T., Kim, S. D., Choi, I. S. (1986). Bubble characteristics and pressure fluctuations in two and three phase fluidised beds. Chemical Engineering; World Congress III, Soc Chem Eng Jpn, 1986, Vol III, 492-495.

Joseph, D. D., Fortes, A. F., Lundgren, T. S., Singh, P. (1986). Nonlinear mechanics of fluidisation of spheres, cylinders and discs in water. Advances in multiphase flow and related problems; Workshop, SIAM, 1986, 101-122.

Kitano, K., Fan, L-S. (1988). Near-wake structure of a single gas bubble in a two-dimensional liquid-solid fluidised bed: solids hold-up. Chem. Eng. Sci., 43 (6), 1355-1361.

Kono, H. O., Ahmadi, A. S., Huang, C.-C. (1987). The prediction of kinetic forces and kinetic collision energy of solid particles in fluidised beds. In New Developments in Fluidisation and Fluid-Particle Systems. 1985 and 1986 AIChE Annual Meetings (Ed. Yang, W. C.), 83 (255), 50-57.

Kono, H. O., Ahmadi, A. S., Suzuki, M. (1986). Kinetic forces of solid particles in fluidised beds. Chemical Engineering; World Congress III, Soc. Chem. Eng. Japan, 1986, Vol III, 540-543.

Lee, J. C., Al-Dabbagh, W. (1978). Three phase fluidised beds: onset of fluidisation at high gas rates. Fluidisation. Proceedings of the Second Engineering Foundation Conference, Cambridge, U. K., 2-6 April 1978.

Mackay, D. J. (1988). Backwashing ensures effective filtration. Opflow, AWWA publication, 14 (10), 4-5.

Moll, H. G. (1986). Expansion of filter media during backwashing. 4th World Filtration Congress. K.VIV, 1986 (1), 8.7-8.11.

*
Muslu, Y. (1987). A new approach to the prediction of fluidisation of filter media. Water Research, 21 (9), 1053-1060.

Norman-Gregory, G. M., Selig, E. T. (1988). Volume change behaviour of vibrated sand columns. A.S.C.E. Journal of Geotechnical Engineering, 115 (3), 289-303.

Pasquarell, G. C., Ackermann, N. L., Shen, H. H., Hopkins, M. A. (1988). Collisional stress in granular flows: Bagnold revisited. A.S.C.E. Journal of Engineering Mechanics, 114 (1), 49-64.

Peters, M. H., Fan, L-S., Sweeney, T. L. (1983). Study of particle ejections in the freeboard region of a fluidized bed with an image carrying fibre optic probe. Chem. Eng. Sci., 38 (3), 485-487.

Peterson, D. A., Tankin, R. S., Bankoff, S. G. (1987). Bubble behaviour in a three-phase fluidised bed. Int. J. Multiphase Flow, 13 (4), 477-491.

Quaye, B. A. (1987). Predicting optimum backwash rates and expansion of multi-media filters. Water Research, 21 (9), 1077-1087.

Rajapakse, J. P. (1988). Pre-filtration of high turbidity waters. Ph.D. Thesis, University College London, London University, U.K..

Regan, M. M., Amirtharajah, A., (1984). Optimization of particle detachment by collapse-pulsing during air scour. Proceedings of Conference of the American Water Works Assoc., Dallas, Texas, June 1984 (16pp).

Roberts, J. (1986). Collapse-pulsing in sand filters using air/water combinations. Chemeca 86: 14th Australas Chem. Eng. Conf., 399-404.

Saxena, S. C., Patel, D.C., Kathusia, D. (1987). An image-carrying fibre optic probe to investigate solids distribution around an immersed surface in a gas-fluidised bed. AIChE J., 33 (4), 672-676.

*Moll, H. G. (1990). Effectiveness of backwashing with air and water. Proceedings of the Vth World Filtration Congress, Nice, France. June 1990.

Schulenberg, T., Müller, U. (1987). An improved model for two-phase flow through beds of coarse particles. Int. J. Multiphase Flow, 13 (1), 87-97.

Shen, H. H., Hopkins, M.A., Ackermann, N. L. (1988). Modelling collisional stresses in a dense fluid-solid mixture. J. Fluids Eng. Trans. A.S.M.E., 110 (1), 85-90.

Sholji, I., Johnson, F. A. (1987). Comparison of backwash models for granular media. A.S.C.E. Journal of Environmental Engineering, 113 (3), 532-549.

Sholji, I. (1987). Expansion of granular filters during backwashing. A.S.C.E. Journal of Environmental Engineering, 113 (3), 516-531.

Silvester, N. R., Sleigh, M. A. (1985). The forces on microorganisms at surfaces in flowing water. Freshwater Biology, 15, 433-448.

Simmonds, M. A. (1963). Public water supplies of Queensland, Australia. Journal of the American Water Works Assoc., 55 (8), 1044-1080.

Song, G-H., Fan, L-S. (1986). Rheological behaviour of a gas-liquid-solid fluidized bed. Chemical Engineering; World Congress III, Soc. Chem. Eng. Japan, 1986, Vol III, 504-507.

Syamial, M. (1987). Particle-particle drag term in a multiparticle model of fluidisation. Report DOE-MC-21353-2373, 25pp. (US NTIS DE87006500-GAR).

Tsotsas, E., Schlunder, E. U. (1988). On axial dispersion in packed beds with fluid flow. Chemical Engineering and Processing, 24 (1), 15-31.

Watson, A. M. (1987). Anglian Water / UCL pilot filtration study. Annual report 1987.

Wen, H. Y., Kasper, G. (1989). On the kinetics of particle re-entrainment from surfaces. J. Aerosol Sci., 20 (4), 483-498.

Yang, S-Z. (1986). A correlation of liquid dispersion in three phase fluidised beds. Chemical Engineering; World Congress III, Soc. Chem. Eng. Japan, 1986, Vol III, 496-499.

LIST OF ABBREVIATIONS AND SYMBOLS

ε_e	porosity of expanded (fluidised) bed
ε	porosity of sand bed
μ	absolute viscosity
τ	shear stress
d_{10}	Effective size of grains, 10% finer than this diameter by weight.
d_{60}	60% of grains finer than this diameter by weight.
d_{90}	90% of grains finer than this diameter by weight.
fps	frames per second
GAC	Granular activated carbon
HSV	High Speed Video
K+A+P	kaolin flocculated with alum and polymer (Percol 155)
L. B.	Leighton Buzzard
n	empirical constant in Richardson-Zaki equation
NTU	Nephelometric Turbidity Units
pics/s	pictures per second
Q	Volumetric flow rate, m^3/s (Q_a = volumetric air flow rate)
Re	Reynolds' number
t_{2000}	time for which turbidity peak is greater than 2000 NTU
$t_{a/w}$	turbidity at end of combined air/water wash
t_f	final turbidity of washwater at end of wash
U_c	Uniformity coefficient (= d_{60}/d_{10})
UCL	University College London
v	upward flow velocity
v_g	upward macroscopic gas velocity
v_i	interstitial water velocity
v_l	upward macroscopic liquid velocity
v_{mf}	minimum liquid fluidising velocity
v_s	grain speed
v_w	upward macroscopic water velocity

Appendix I

```
'  This code communicates with the NAC XY Coordinator to receive x, y,
'      time and scene code data from high speed video tapes.
'
'  Data is written on the screen as it is received, and to a data file
'      for later use in calculation of velocities etc.
'
'  Commands are read from the PC keyboard and sent to the XY coordinator
'      Commands are as follows:
'              [space bar] = data out (i.e. read the current data from the
'                                         video screen)
'              N (or n)    = new set of measurements (e.g. new grain)
'              F (or f)    = advance video tape by 1 frame
'              Q (or q)    = quit program
'
' MAIN PROGRAM
'
DECLARE SUB READCOM (A$, M%)
DECLARE SUB DECIPH (A$, M AS INTEGER)
'
'    SET SCREEN ,TURN OFF KEY DISP;CLR SCREEN,CLOSE ALL FILES
40 SCREEN 9, 0: WIDTH 80: KEY OFF: CLS : CLOSE
'    DEFINE NUMERIC VARIABLES AS INTEGER
90 DEFINT A-Z
'   OPEN COMMS TO FILE2 : 600BPS,NO PARITY,7 DATABITS - LINE TO XY
'                                             COORDINATOR
'
160 OPEN "COM2:600,N,7,1" FOR RANDOM AS #1
'    OPEN FILES FOR OUTPUT
180 OPEN "SCRN:" FOR OUTPUT AS #2
   INPUT "ENTER NAME OF CALIBRATION FILE"; C$
   INPUT "ENTER NAME OF OUTPUT FILE"; D$
185 OPEN D$ + ".TXT" FOR OUTPUT AS #3: 'PRINT #3, D$
187 OPEN C$ + ".TXT" FOR OUTPUT AS #4
'   TURN CURSOR ON
200 LOCATE , , 1
400 ON ERROR GOTO 9000
455 calib = 0: M = 2: N = 0
460 PRINT #1, "/I" + CHR$(13) + "/A1" + CHR$(13)
470 PRINT "CALIBRATE X AND Y"
471 PRINT " "
472 PRINT "ENTER 4 POINTS FOR X AND Y CALIBRATION"
475 calib = calib + 1
'
498 A$ = ""

'   SEND KEYBD I/P TO COM LINE
505 B$ = INKEY$: IF B$ = CHR$(32) THEN PRINT #1, "/B" + CHR$(13)
'          when N is typed, four -ve nos are written in the data file.
509            IF B$ = "N" OR B$ = "n" THEN N = N - 1: WRITE #3, N, N, N, N: PRINT N
511            IF B$ = "F" OR B$ = "f" THEN PRINT #1, "/F1" + CHR$(13): GOTO 498
512               IF B$ = "Q" OR B$ = "q" THEN PRINT #1, CHR$(13): CLOSE #3: PRINT "":
PRINT "END": PRINT "": STOP
513 IF EOF(1) THEN 505         'If buffer empty check key in
514 CALL READCOM(A$, M)          'Sub to display data from X-Y on screen and write to file
515 IF LEN(A$) < 35 THEN GOTO 505
'
'    the following checks that there are 4 calibration pts
680 IF calib < 4 THEN 475
'      when 4 pts entered starts reading data from measurements
690 IF calib = 4 THEN CLS : calib = 5: PRINT "ENTER DATA": M = 8
'     CHECK FOR KEYBD I/P AGAIN
710 GOTO 498
'     IF ERROR,PRINT ITS NUMBER AND RETRY
9000 PRINT "ERROR NO."; ERR: RESUME


SUB DECIPH (A$, M AS INTEGER)
'
' This subroutine deciphers the data from the xy coordinator
'
'   TO LOOK FOR COMMAS SEPARATING VARIABLES IN STRING
5020 K = 0: Q$ = RIGHT$(A$, LEN(A$) - 1)
'  Moves along character string
```

```
5025 FOR K = 1 TO M
5030 PTN = 0: X$(K) = ""
5032 PTN = PTN + 1
5035 IF PTN > LEN(Q$) THEN 6060
5040 CAP = INSTR(PTN, Q$, ",")
5050 IF CAP = 0 THEN 5032
5060 X$(K) = LEFT$(Q$, CAP - 1): Q$ = RIGHT$(Q$, LEN(Q$) - CAP)
5065 NEXT K

5067 IF M = 2 THEN GOSUB 6010: GOTO 6060

5070 X = VAL(X$(1)): Y = VAL(X$(2)): N = VAL(X$(3)): SC = VAL(X$(4)): O = VAL(X$(5))
5075 T& = (VAL(X$(6)) * 100000) + (VAL(X$(7)) * 1000) + VAL(X$(8))
5077 PRINT #2, "X="; X, "Y="; Y, "SC="; SC, "T="; T&; "MS"
5079 WRITE #3, X, Y, SC, T&
6000 GOTO 6060
'
6010 '    SUBROUTINE TO CALCULATE X AND Y OF CALIBRATION POINTS
'         Writes 4 pairs of x and y to calibration file
6020 XC = VAL(X$(1)): YC = VAL(X$(2))
6030 WRITE #4, XC, YC
6040 PRINT XC, YC
6050 RETURN
6060 END SUB


SUB READCOM (A$, M)
'   This subroutine reads the data from the xy coordinator as a string of
'      characters from the communications buffer

572 X$ = INPUT$(LOC(1), #1): A$ = A$ + X$
'      READ CONTENTS OF COM BUFFER
'      REMOVE LINEFEEDS and carriage rtns
620 LFP = 0: PSN = 1: CRN = 0
'      LOOK FOR LINE FEED AND RETURNS
630 LFP = INSTR(PSN, A$, CHR$(13))
635 CRN = INSTR(PSN, A$, CHR$(10))
637 IF CRN > 0 THEN MID$(A$, CRN, 1) = ""
640 IF LFP > 0 THEN MID$(A$, LFP, 1) = ""
641 PSN = PSN + 1
642 IF PSN >= LEN(A$) THEN GOTO 646
645 GOTO 630
646 IF LFP = 0 AND CRN = 0 AND LEN(A$) < 36 THEN GOTO 675
'      DISPLAY COM I/P
660 PRINT #2, A$                     ' prints data on screen

'      NOW DECIPHER THE MESSAGE IN A$
670 CALL DECIPH(A$, M)
675 END SUB
```

Appendix II

```
'This program reads in the x, y and time data obtained via the x-y coordinator
' and calibrates the x and y values before calculating velocities, means
' and variances of velocities


DECLARE SUB MAXMIN (max!, min!, DV(), J)
DECLARE SUB AV (J, SUMVDT, SUMV2DT, TT, max, min, VALL2TOT, SUBMEAN, TGRAINS,
SMEANSQ)
DECLARE SUB CALIB (CX!, CY!)
DECLARE SUB DVEL (I, t(), X(), Y())

15 DIM X(800), Y(800), SC(800), t(800)
20 SCREEN 9: CLS : VIEW: KEY OFF: CLOSE

  INPUT "ENTER NAME OF DATA FILE WITH X,Y AND TIME INFO"; D$
   OPEN D$ + ".TXT" FOR INPUT AS #3
   OPEN "CHKDATA.TXT" FOR OUTPUT AS #2

   CALL CALIB(CX, CY)'    Works out X and Y calibration values
   IF CX = 0 OR CY = 0 THEN PRINT "ERROR: CALIBRATION VALUE OF ZERO": GOTO 160
   '
     '    Loop to read in and calibrate X and Y coordinates
   PRINT #2, "CHECK DATA - X,Y,SC,T"
  '
  '   loop to read in data from DATA FILE, output from DRNEW.BAS
100 FOR I = 1 TO 800
105 IF EOF(3) THEN GOTO 155
110 INPUT #3, X(I), Y(I), SC(I), t(I)

'   Calibrate x and y values using calculated calibration values
120 X(I) = 1000 * X(I) / CX: Y(I) = 1000 * Y(I) / CY   'calibrate x and y to mm
' to check data has been read correctly - time errors affect velocities
     PRINT #2, t(I), t(I) - t(I - 1)
150 NEXT I

155 CALL DVEL(I, t(), X(), Y())
160 CLOSE
```

```
SUB AV (J, SUMVDT, SUMV2DT, TT, max, min, VALL2TOT, SUBMEAN, TGRAINS, SMEANSQ)

'             Calculates means, variance etc.

J = J + 2
PRINT #1, "VAV ="; SUMVDT / TT; "-----"; "VAR="; (SUMV2DT / TT) - (SUMVDT / TT) ^ 2;
"MAX="; max; "MIN="; min

'    TGRAINS is total time grain is measured for, which is added up
'          for grand mean of all grains.
'    VALL2TOT = v squared delta t
TGRAINS = TGRAINS + TT: VALL2TOT = VALL2TOT + SUMV2DT
SUBMEAN = SUBMEAN + (SUMVDT) ' to be used in grand mean calculation
SMEANSQ = ((SUMVDT ^ 2) / TT) + SMEANSQ
SUMVDT = 0!: TT = 0!: SUMV2DT = 0!: max = 0!: min = 1E+07 ' resets to zero
'                                                    for next grain
END SUB
```

```
SUB CALIB (CX, CY)
'
'    Calculates calibration values for x and y, using 4 pairs of coord's
INPUT "ENTER NAME OF FILE WITH CALIBRATION VALUES"; C$
OPEN C$ + ".TXT" FOR INPUT AS #5
FOR I = 1 TO 4
        INPUT #5, X(I), Y(I)
        PRINT X(I), Y(I)
NEXT I
CX = (ABS(X(2) - X(1)) + ABS(X(3) - X(4))) / 2
```

```
CY = (ABS(Y(4) - Y(1)) + ABS(Y(3) - Y(2))) / 2
PRINT "CX="; CX, "CY="; CY
END SUB
```

```
SUB DVEL (I, t(), X(), Y())

        'Calculates velocities from x,y and time data, then calculates
        ' the mean etc. for each grain, followed by the overall mean and
        '  variance.

    INPUT "ENTER NAME OF FILE FOR OUTPUT VELOCITIES"; v$
    OPEN v$ + ".TXT" FOR OUTPUT AS #1: PRINT #1, v$

    'THIS FILE CONTAINS DV(J) FOR HISTOGRAM PLOTTING......
    OPEN "H" + v$ + ".TXT" FOR OUTPUT AS #4

    DIM DVX(800), DVY(800), DV(800), THETA(800), DV2(800)
    PRINT #1, "DVX(MM/S), DVY(MM/S), DV(MM/S), THETA, T(MS)" ' labels columns

    'set variables to zero:
     J = 0: SUMVDT = 0: TT = 0: SUMV2DT = 0: VALL2TOT = 0: TGRAINS = 0: GMEAN = 0:
GVAR = 0
     SUBMEAN = 0: SMEANSQ = 0' Mean  AND MEAN SQD for each individual grain which is
summed

     '  Start of vel calculations
1045     J = J + 1

    ' This routine checks for the minus signs that separate grains
    M$ = STR$(X(J))
    IF J >= I THEN 2000
     IF LEFT$(M$, 1) = "-" AND TT > 0 THEN CALL AV(J, SUMVDT, SUMV2DT, TT, max, min,
VALL2TOT, SUBMEAN, TGRAINS, SMEANSQ)
    IF (t(J) - t(J - 1)) = 0 THEN DVX(J) = 0: DVY(J) = 0: PRINT " TIME ERROR": GOTO 1090
    IF t(J) <= 0 OR t(J - 1) <= 0 THEN PRINT "TIME ERROR": GOTO 1045

     ' calculates delta vx and delta vy
1050 DVX(J) = (X(J) - X(J - 1)) / (t(J) - t(J - 1))
1070 DVY(J) = (Y(J) - Y(J - 1)) / (t(J) - t(J - 1))

    ' calculate grain direction
    IF DVX(J) = 0 THEN THETA(J) = PI / 2: GOTO 1090
    THETA(J) = (ATN(DVY(J) / DVX(J))) * 180 / 3.142

  ' sum delta t's
1090 TT = TT + (t(J) - t(J - 1))
    DV2(J) = (DVX(J) ^ 2) + (DVY(J) ^ 2)
    DV(J) = SQR(DV2(J))          ' actual magnitude of velocity

    'call subroutine to calculate max and min velocity
    CALL MAXMIN(max, min, DV(), J)

    'sum the v squareds times delta t
    SUMV2DT = SUMV2DT + (DV2(J) * (t(J) - t(J - 1)))

    ' sum vels times delta t
    SUMVDT = SUMVDT + (DV(J) * (t(J) - t(J - 1)))

     ' write velocity data to #1 (the velocity data file)
1120 PRINT #1, DVX(J); DVY(J); DV(J); THETA(J); t(J - 1)

    ' this writes velocities to file for statistical analysis
    N = 0
    IF t(J) - t(J - 1) = 0 THEN 1300
    N = (t(J) - t(J - 1)) / 5
    FOR K = 1 TO N
       PRINT #4, DV(J)
    NEXT K

1300 GOTO 1045        '     Returns to beginning of vel loop to continue calculations

2000 IF TT = 0 THEN PRINT "TIME ERROR": GOTO 2020

2010 CALL AV(J, SUMVDT, SUMV2DT, TT, max, min, VALL2TOT, SUBMEAN, TGRAINS,
SMEANSQ)
2020 PRINT "END OF DATA"
```

```
    'calculates mean and variance for all grains
    GMEAN = SUBMEAN / TGRAINS' gives weighted mean of all grains
    GVAR = (VALL2TOT / TGRAINS) - (GMEAN ^ 2) '    grand variance of all grains
    VAROFMS = (SMEANSQ / TGRAINS) - (GMEAN) ^ 2  '    variance of means
    PRINT #1, "**************************"
      PRINT #1, "GRAND MEAN = "; GMEAN; "VARIANCE OF MEANS = "; VAROFMS; "
OVERALL VARIANCE = "; GVAR
CLOSE
END SUB


SUB MAXMIN (max, min, DV(), J)
'
'       Calculates maximum and minimum velocities for each grain
        IF DV(J) > max THEN max = DV(J)
        IF DV(J) < min THEN min = DV(J)
END SUB
```

Appendix III

Video Tape Description

The contents of the video tape are described below. The standard playback speed on the HSV is at 1/3 real time (i.e 67 fps for 200 fps recording). All scenes are played back at this rate unless otherwise stated.

The graticule, as described in section 3.3, consists of two pairs of parallel lines 1 mm apart. Scene code followed by time information are displayed at the top of the screen; these will be used to identify particular events in the description below. The first two pairs of time digits represent hundreds of seconds and seconds, respectively; the last three digits are milliseconds. It can be observed that frames are in increments of 5 ms due to the 200 fps recording rate. Each frame has a field of view of about 10 grains.

The total run time of the tape is 20 minutes.

Scene Code	Time	Description
		Clean bed
503	00.03.040	v_w = 20 m/h = 87 % v/v_{mf}. No bed expansion or grain movement can be observed.
	00.10.2...	End of sequence.
504	00.00.060	v_w = 23 m/h = v_{mf}. Bed is at the point of incipient fluidisation. There is intermittent grain movement. Periods of rest and high activity can be observed.
	00.15.000	End of sequence.
507	00.41.000	v_w = 32 m/h = 139 % v/v_{mf}. 6 % expansion. Periods of low and high activity are still observed but grains exhibit more higher velocities.
	00.58....	End of sequence.
	00.67....	Replay continues at 2 fps. Individual grain behaviour can be observed in more detail. Note grain rotations and collisions. Groups of grains may move together across the field of view or sometimes some remain stationary while others move.
	00.68.580	End of 2 fps sequence.

cont'd......

Scene Code	Time	Description
		Kaolin clogged bed
602	00.19....	View of clogged bed prior to opening backwash valves. Note the white kaolin deposits on the sand grains.
	00.20....	Start of backwash, v_w = 7.5 m/h = 33 % v/v_{mf}. Deposits are detached by fluid shear forces as soon as backwash valves are opened.
	00.22.000	Slight grain movement, particularly of the left grain, can be observed as deposits detach from grain surfaces. This movement, which was not observed in a clean bed at this flow rate, may result from the reduced pore space giving rise to higher shear stresses and uneven velocity distribution.
	00.25.700	More slight grain movement followed by settlement.
	00.50....	After about 30 s of wash the washwater appears to be cleaner and the individual grains look clean apart from clumps of deposit that are trapped in regions where the shear stress is insufficient to cause detachment.
	00.61.5..	End of sequence.
	00.20.280	Start replay of first 1-2 s at start of wash at 2 fps.
	00.20.330	Deposit detaches in lower left of grid square as backwash flow starts.
	00.20.5..	Many deposits are seen detaching and being carried away by the flow.
	00.21.8..	State of bed after 1.5 s of wash. Many deposits have detached and flow probably has not reached prescribed rate. Replay speed increased from 2 fps, then end of scene.
111	00.03.400	Showing clogged bed prior to start of backwash.
	00.04.735	Backwash flow starts, v_w = 30 m/h = 130 %v_{mf}. Bed expands rapidly and large amounts of deposit detach instantly. Grain movement is vigorous and the upflowing water is clouded by the concentrated suspension of detached deposits. Deposits appear to leave grain surfaces almost instantaneously and are resuspended in the upflowing water.
	00.24....	End of sequence.
	00.04.600	Repeat of above start of wash in slow motion at 2 fps.
	00.04.720	Deposits beginning to detach in lower left pore as the backwash valves are opened.
	00.04.750	Large floc in lower centre of screen detaches and begins to move upwards.
	00.04.8..	Bed begins to expand, the grains move upwards and many deposits are detached by the shear forces from the flow.
	00.05.885	End of 2 fps sequence.

cont'd......

Scene Code	Time	Description
164	00.40.7..	Clogged bed prior to backwashing.
	00.42.650	Start of combined air and water wash at collapse-pulsing; v_w = 9.2 m/h = 40 %v_{mf}, v_a = 54.8 m/h. The whole bed commences agitation immediately and individual grains begin rapid movement, with similar velocities to those in a fluidised bed. The whole bed appears to be pulsating. Deposits are detached at the start of the wash by fluid shear forces and are resuspended. Flushing out of deposits is a slow process due to the low water rate, but grains appear clean. The high grain velocities give rise to high shear stresses on the grain surfaces, as well as collisions between grains. Groups of grains exhibit circulatory motion, which may be due to the collapse of grains in the wake of passing air as predicted by Amirtharajah (1984). The passage of air in front of the borescope tip gives rise to dark patches on the video, this is because the light from the boresope is not reflected back.
	00.72.7..	End of sequence.
	00.42.400	Replay of air and water wash sequence at 2 fps. It can be observed that occasionally grain motion is so rapid that grains appear blurred even at 200 fps recording.
	00.42.6..	Deposits begin to detach as soon as the air and water valves are opened. The sweeping circulatory movement of the grains associated with passing air can be seen in more detail. This motion is very rapid and often results in blurred images of the grains, i.e. 200 fps is not sufficient to freeze the motion.
	00.43.380	End of 2 fps sequence.
	01.63.1..	Showing the state of the bed after 120s of combined air and water wash. The grains appear clean although the upflowing water exhibits some residual turbidity. It can be noticed that the 1mm square graticule has become worn after repeated air scour experiments. Air bubbles pass the borescope tip very rapidly and often the transition from a view of a bubble to the sand grains in its wake takes place between subsequent frames, i.e. in < 5 ms. The collapse-pulsing behaviour can be observed. The out of focus grains can often be seen behind the dark air cavities.
	01.82.3..	End of sequence.
	01.82.390	Play continues at 2 fps so that grain behaviour can be seen in more detail. Again the blurring of rapidly moving grains can be seen. As air passes the fluid film between the air and the grain surface can be observed. This film moves rapidly and so could generate high shear stresses.
	01.83.2..	An air bubble can be clearly seen, followed by the predicted rapid grain movement.
	01.84.040	End of 2 fps sequence. Freeze on a passing air bubble. The very last scene shows the movement of the cursor from the XY Coordinator moving across the screen from lower left to top right. Note the changing x and y coordinates displayed at the bottom of the screen. This x, y and time (displayed at top of screen) information was used for the velocity measurements. End of video.

Appendix IV

Publications and presentations resulting from the work in this thesis:

Amirtharajah, A., Fitzpatrick, C. S. B., Ives, K. J. (1990). Endoscope studies on optimum backwashing of filters. Presented at American Water Works Assoc. Annual Conference, June 17-21, 1990, Cincinnati, Ohio.

Fitzpatrick, C. S. B. (1990). Detachment of deposits by fluid shear during filter backwashing. Proceedings of IAWPRC - IWSA Joint Specialist Conference, Jönköping, Sweden 24-26 April 1990, Water Supply, Vol. 8, 177-183.

Fitzpatrick, C. S. B. (1990b). The mechanisms of deposit detachment during filter backwashing. Poster selected for presentation at the European Research Conference on Particles in Natural Waters and in Water Technology, Il Ciocco, Italy, 3-7 September 1990. Abstract published in proceedings.

Ives, K. J., Fitzpatrick, C. S. B. (1989). Detachment of deposits from sand grains. Colloids and Surfaces, 39, 239-253.

ENDOSCOPE STUDIES ON OPTIMUM BACKWASHING OF FILTERS WITH AIR SCOUR

by

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Note: If accepted a part of the presentation will include video material from the backwash studies

An abstract for presentation of a paper at the Research Sessions of the 1990 AWWA Annual Conference

ENDOSCOPE STUDIES ON OPTIMUM BACKWASHING
OF FILTERS WITH AIR SCOUR

Introduction

In recent times Ives and co-workers have developed the use of rigid optical fiber endoscopes for the direct visual observation and measurement of processes occurring within a filter bed. In previous studies on filtration, the endoscope technique has provided direct visual evidence for the characteristics of the deposits filling the crevices and depressions of filter grain surfaces, for the detachment of deposits and the presence of wormholes within clogged media. Observations have also been made by using a high-speed TV camera operating at 200 frames per second to investigate the detachment of clay particles from filter grains during backwashing at sub-fluidization and fluidization backwash using water only.

Amirtharajah and co-workers have studied backwashing filters with air scour and concluded that the best cleaning of media occurs with simultaneous air and sub-fluidization water flow when a condition termed collapse-pulsing occurs within the bed. A theoretical model which predicts collapse-pulsing was developed by equating the air pressure within a bubble to the soil stresses in an active Rankine state plus the pore-water pressures.

The present research combines the theoretical aspects of collapse-pulsing with an experimental filter system having an endoscope, high speed video system with freeze frame capability for visual observations and an XY Coordinator with computer hardware and software which enabled the determination of velocities of filter grains during air scour. The major objective of the research was to determine the optimum rates of air-water wash and associate it with the collapse-pulsing theory.

Theoretical Aspects

The different phases of upward motion of concurrent air and water through a filter bed is complex, but systematic patters of flow behavior are discernible. The patterns of behavior are expressed in terms of the fluidizing velocity V expressed as a percentage of the minimum fluidization velocity V_{mf}.

At water flow rates of (V/V_{mf}) = 30 to 50%, which are dependent on the corresponding air flow rates, the air cavity that forms at the bottom of the bed causes the water flow stream lines to bend around the cavity. This results in the air from the cavity to flow into a tubular channel at the top, the pressure within the cavity declines rapidly, and due to a reduction of the horizontal stresses in the sand, the sand around the cavity fails locally in an active Rankine state. When this condition occurs throughout the bed, it is termed collapse-pulsing. Amirtharajah showed that by equating the pressure within the cavity to the horizontal stress in the soil-water matrix the following general equation for collapse-pulsing may be derived.

$$P_1 - \frac{2T}{r} - k\,Q_a^2 = \tan^2\left(45 - \frac{\phi}{2}\right)\left[Z\gamma_b - Z\gamma_w(s_g - 1)(1-\epsilon_o)\frac{V}{V_{mf}}\right]$$

$$+ \gamma_w\,(Z + H_1) + \gamma_w\,Z\,(s_g - 1)(1-\epsilon_o)\frac{V}{V_{mf}} \quad \ldots\ldots(1)$$

in which P_1 = gage pressure, T = surface tension, r = radius of cavity surfaces, Q_a = air flow rate, k = coefficient, ϕ = friction angle, Z = depth of media, γ_b = buoyant unit weight, γ_w = unit weight of water, S_g = specific gravity of grains, ϵ_o = porosity of fixed bed and H_1 = height of water above media. For a specific filter system the above equation collapses to,

$$\left[\%\,\frac{V}{V_{mf}}\right] + a\,Q_a^2 = b \quad \ldots\ldots(2)$$

in which a, b = constants. The equation used for the experimental studies which defined the collapse-pulsing condition was,

$$\left[\%\,\frac{V}{V_{mf}}\right] + 0.35\,Q_a^2 = 44.3 \quad \ldots\ldots(3)$$

in which Q_a= airflow rate in scfm/sq ft.

Experimental Techniques

The model filter apparatus consisted of a perspex column 0.115 m (4 in) diameter and 1 m (39 in) high, with a bed of sieved sand (0.5 - 1.0 mm). A suspension of kaolin clay in London tap water was filtered to clog the bed with 5 kg/m^2 of clay. The filter was backwashed with a combination of air plus water followed by water alone and the process was recorded on video tape by means of a rigid optical fibre endoscope. This technique has been described by Ives and Fitzpatrick and gives an image with a normal magnification of 100. Backwash water was collected and samples analyzed to determine the mass of kaolin detached during backwashing. Additionally backwash water within the bed was sampled continuously using a flow through turbidimeter and the analogue signal recorded. A total set of 20 experiments were completed with four different air flow rates (Q_a = 2,3,4 and 5 scfm/sq ft). At each air flow rate 5 different water flow rates were used (V/V_{mf} = 18, 30, 42-39*, 50 and 60). The (V/V_{mf}) value used for the middle test was specifically calculated for collapse-pulsing rates using Eq. 3. Using several frozen single frames and the XY Coordinator, mean velocities and variances of these velocities were calculated for 10 sand grains at each combination of air and water flow rates. A sand shear box and the endoscope technique was also used to measure the velocities of sand grains as they collapsed under water in an active Rankine state.

Results and Discussion

Figs. 1 to 3 illustrate the effectiveness of backwash for combined air-water wash in terms of the time for cleaning to a fixed turbidity and the turbidity at the end of air-water wash. It is clearly seen that the middle test corresponding to (V/V_{mf}) = 39 to 42% provides optimum cleaning and these are the collapse-pulsing conditions. Fig. 4 shows that the collapse-pulsing condition is also close to (but not exactly the same as) the point of maximum for the velocities and variances of the velocities of the grains. This analysis has only been completed for a Q_a rate = 3.0 scfm/sq ft and other similar analyzes are being completed. Fig. 5 shows three dimensional plots of the cleaning efficiency in terms of mass of kaolin removed and 3-D composites of Figs. 1 to 3. Fig. 5 shows a ridge in cleaning efficiency and valleys in time and turbidity corresponding closely to the collapse-pulsing condition. In addition, maximum velocities of grains measured from the air scour tests are similar to the average velocities from the shear box tests. A slow motion visual examination of the videos with air-water wash indicates that the whole bed pulsates and grain movement is much more violent with rapid changes in magnitude and direction compared to water fluidization alone. These videos will be a part of the presentation.

The high speed endoscope studies confirm the validity of the collapse-pulsing concepts and demonstrates that the optimum air-water wash rates for design may be computed from collapse-pulsing theory.

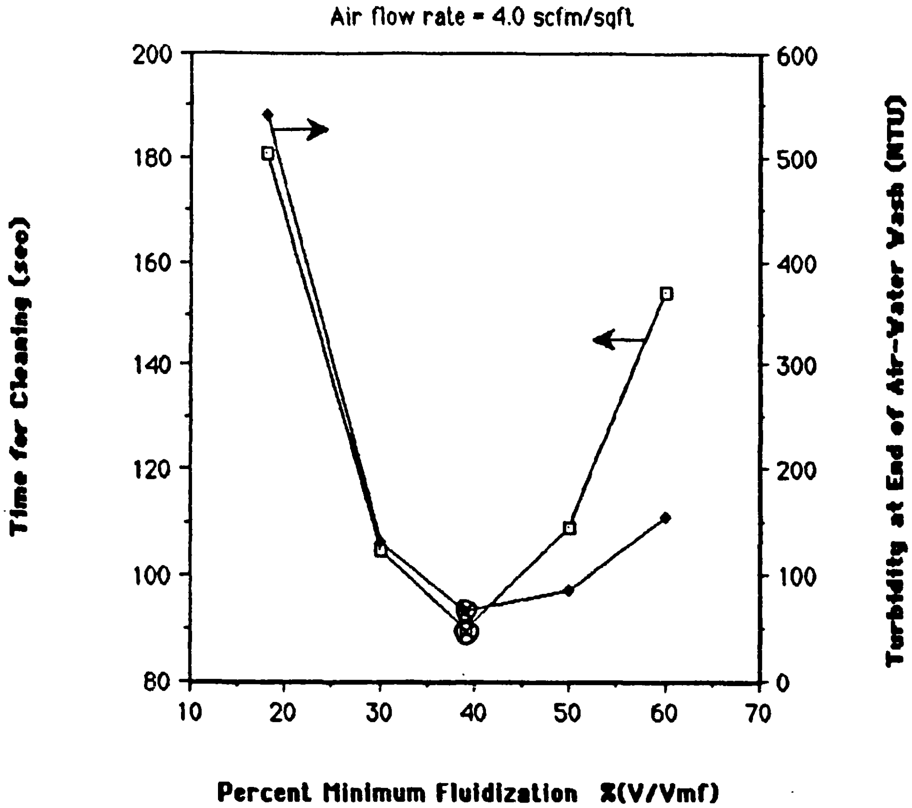

Fig. 1. Time for Cleaning and Turbidity as Functions of Percent Minimum Fluidization for Air Flowrate of 4.0 scfm/sq ft (73.4 m/h).

⊗ Collapse-Pulsing Conditions

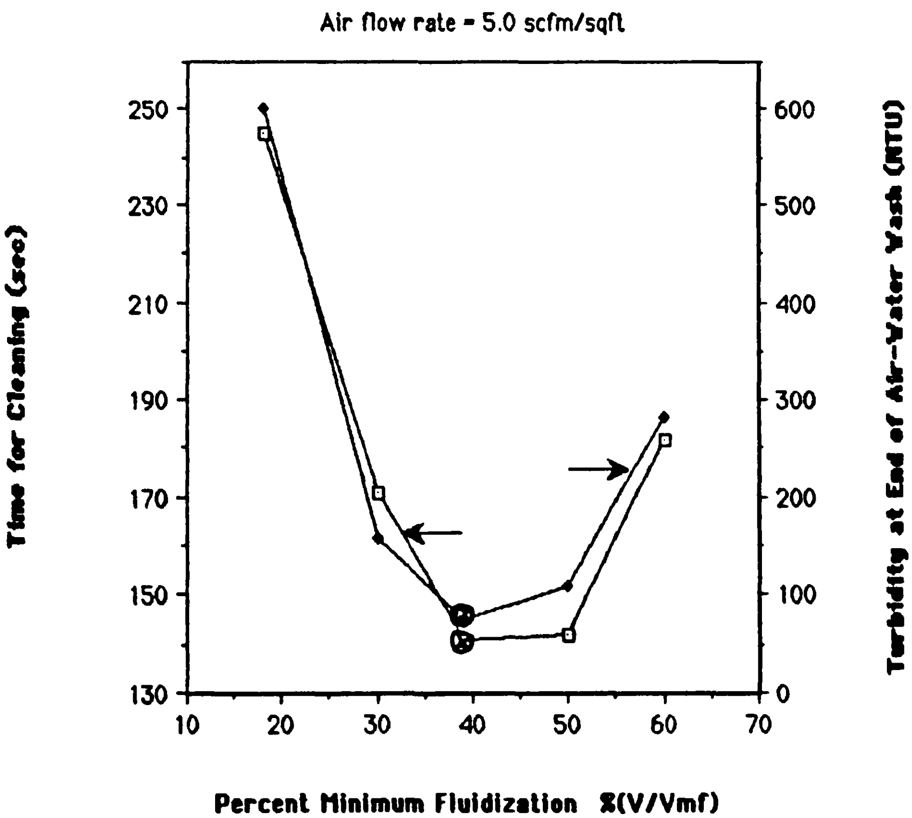

Fig. 2. Time for Cleaning and Turbidity as Functions of Percent Minimum Fluidization for Air Flowrate of 5.0 scfm/sq ft (91.3 m/h).

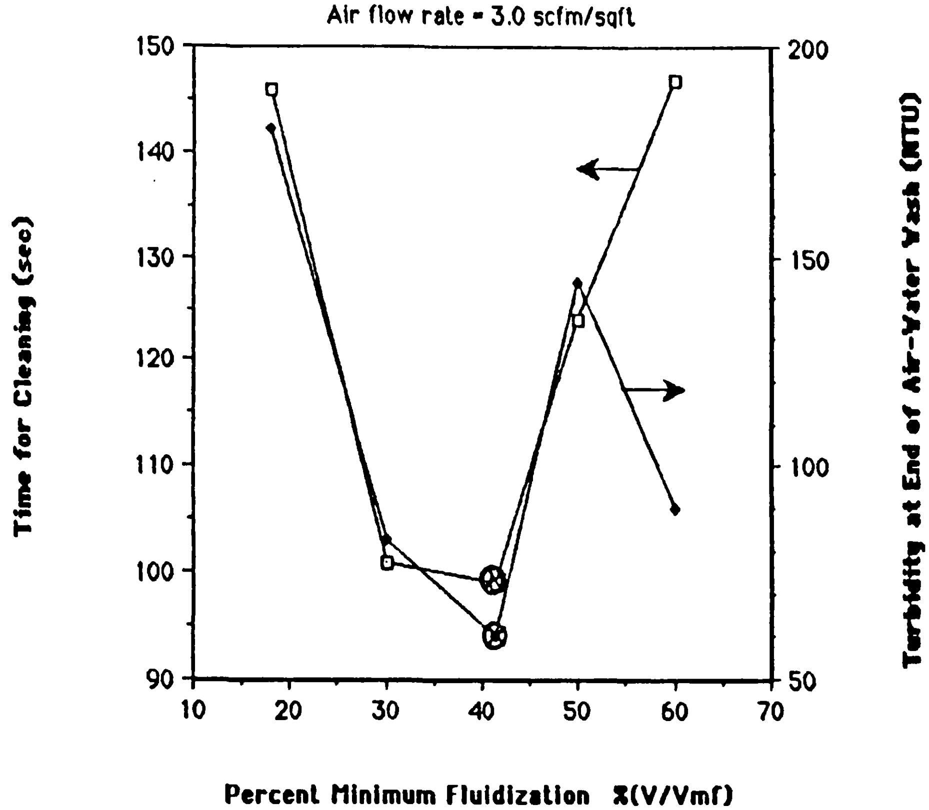

Fig. 3. Time for Cleaning and Turbidity as Functions of Percent Minimum Fluidization for Air Flowrate of 3.0 scfm/sq ft (54.9 m/h).

⊗ Collapse-Pulsing Conditions

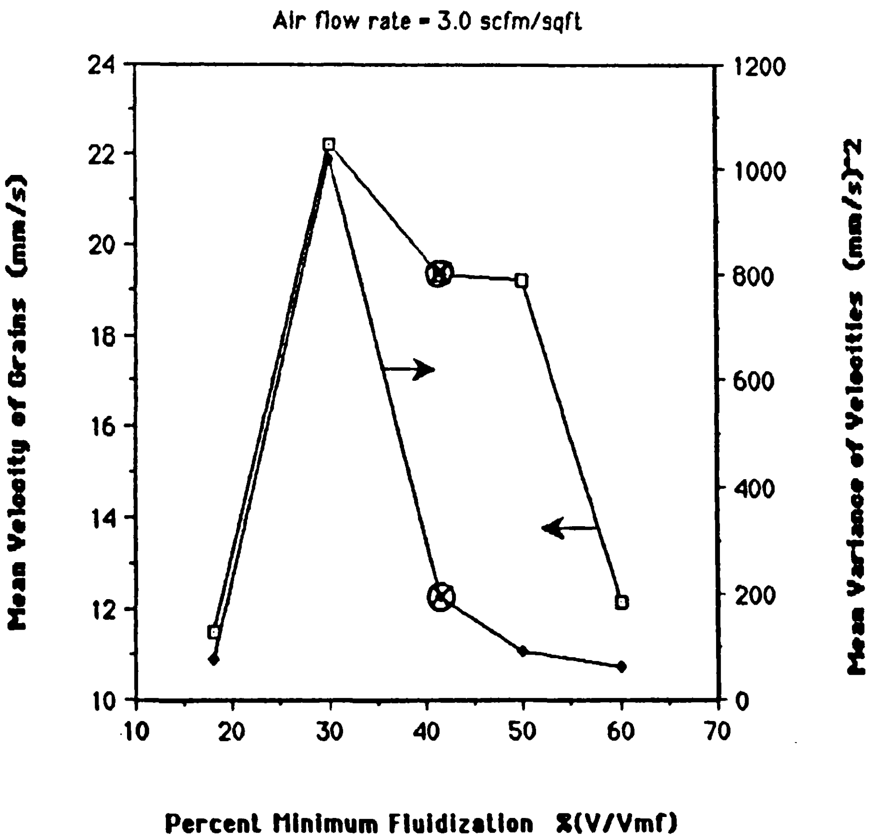

Fig. 4. Mean and Variance of Velocities of Filter Grains as Functions of Percent Minimum Fluidization for Air Flowrate of 3.0 scfm/sq ft (54.9 m/h).

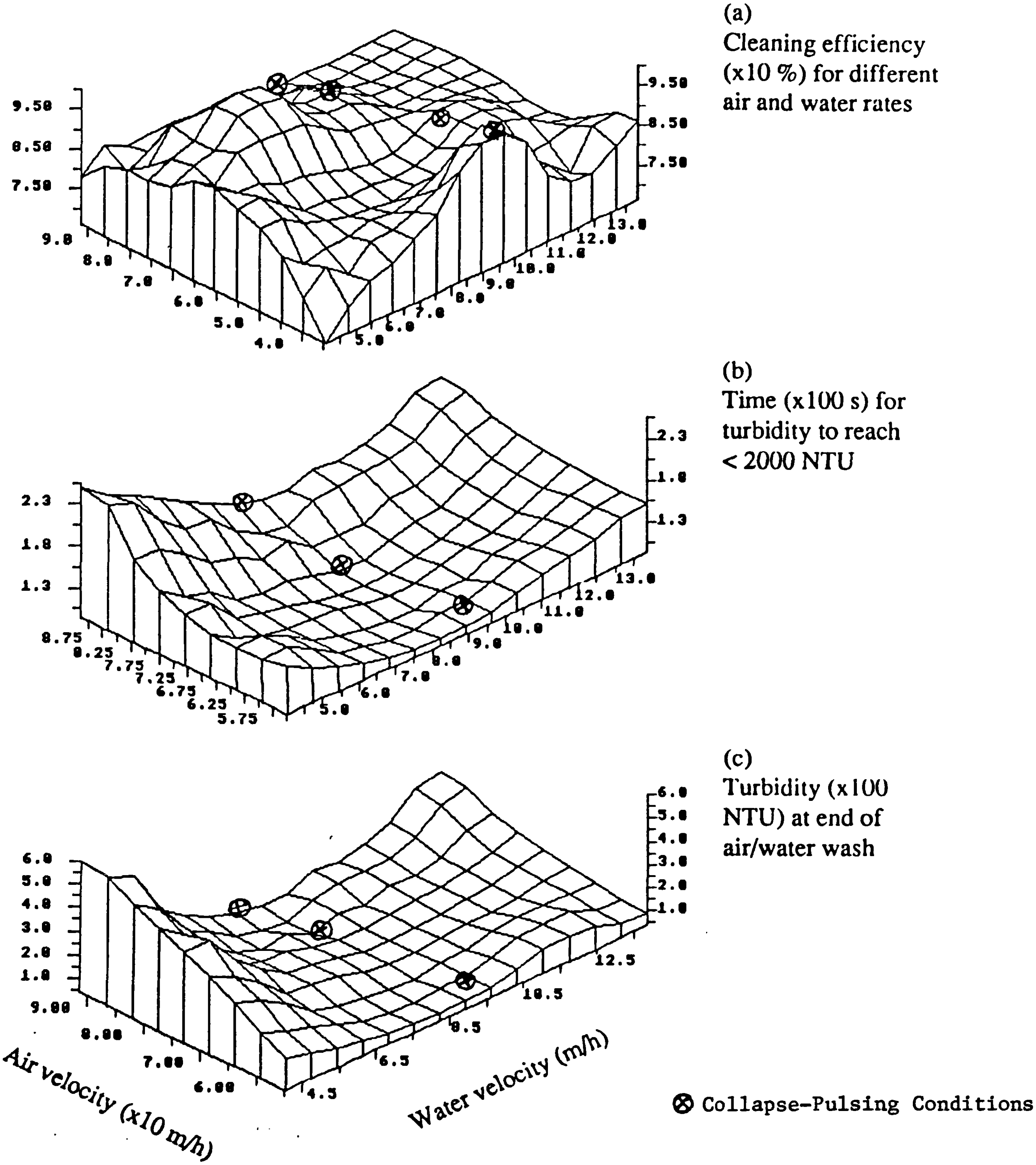

Fig. 5. Results of Backwashing Kaolin Clogged Bed with 5 Minutes Combined Air and Water Wash, Followed by 3 Minutes Fluidizing Water Wash.

Detachment of deposits by fluid shear during filter backwashing

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ABSTRACT

Filter backwashing mechanisms have been investigated using a borescope and high speed video camera and recorder (operating at 200 or 400 frames/s). The experiments were done using a model filter column filled with standard filter sand and clogged with a suspension of kaolin clay in tap water. Results of the experiments, from solids measurements and high speed video recordings, show that it is possible to detach ~90% of kaolin deposits by backwashing with water only for about 10 minutes, where the dominant detachment mechanism is fluid shear. Experiments have also been conducted using simultaneous air and water wash followed by a fluidising water wash and these have shown that maximum efficiency is around the air and water flow rates which satisfy the collapse-pulsing condition, giving ~90% removal efficiency, for the wash rates and durations used.

INTRODUCTION

The process of backwashing deep bed filters is important for maintaining efficient operation. Various techniques are used to remove deposits from the grains within the bed but all involve the upward flow of water which may cause full, or partial, fluidisation of the grains, either throughout or during the final stage of the wash, and deposits are washed out. Traditional American practice is to use auxiliary surface water jets compared with the British and European practice of using air scour in conjunction with water washing. Air scour is now taking over in North America but throughout the world it is employed in different ways: air scour may be with, or without, concurrent water flow, followed by a subsequent water wash; flow rates and durations vary and may not be used in the most efficient combination. Ineffective backwashing leads to poor filter performance.

Most research on the filter washing process has concentrated on the fluidisation behaviour of the granular bed, backwashed with water only (e.g. recent work by Moll (1986), Dharmarajah and Cleasby (1986), Quaye (1987) and Sholji (1987). These do not take into account the use of air scour or the adhesive properties of the deposits and the forces required to detach them.

Huang and Basagoiti (1989) developed a model to predict solids dislodgment during the filter backwashing operation. They used a parameter, K, to characterise the adhesive properties of different deposits and performed experiments to see how easily they are removed during backwashing with water only. No experiments were done using air scour.

An investigation into backwashing mechanisms has been undertaken, using optical fibre borescopes and high speed video (HSV) recording, to try and ascertain what happens inside the bed during the backwashing process. In addition mass balance techniques have been used to obtain information on backwashing efficiency at different rates and duration of water flow and combined air water flow and these compared with theory. Estimated values have been obtained for the fluid shear stresses on the deposits during the washing process.

DETACHMENT MECHANISMS

There has been much discussion about the forces causing deposit detachment during the backwashing process. For water wash, Amirtharajah (1978) concluded that particle collisions were negligible in a fluidised sand bed and that the principal mechanism of cleaning is fluid shear. He developed a theory that predicts the maximum fluid shear at porosities between 0.65 and 0.70 (40 - 50 % expansion for graded sand) when there is maximum turbulence. This optimum expansion is constrained by the fact that particulate fluidisation is an inherently weak cleaning process because of limited abrasion between grains.

Evidence in support of the fact that particle collisions are not significant during fluidisation includes (i) the observation that during laboratory experiments there is no abrasion of experimental filter columns made from perspex (plexiglass), (ii) in order to maintain the grains in a fluidised state there needs to be flow of a thin film of liquid around each grain, and (iii) if the grains actually collided then there would be an upwardly decreasing particle density instead of the abrupt change that is observed at the top of the bed.

To improve cleaning efficiency, it is important to use techniques that cause abrasion between grains, assuming fluid shear on its own is insufficient for detaching the more adhesive deposits. Air scour and surface wash should have this effect and so enhance the cleaning process.

The passage of air bubbles through the sand bed causes rapid movement of the grains as the bubbles pass. The sand grains and adhering deposits collapse in the wake behind a bubble at high velocity. The behaviour of the bed varies for different combinations of air and water flow rates as described by Hewitt and Amirtharajah (1984) and, for certain combinations of flow rates, the bed behaves in a way which has been described as collapse-pulsing, for which a theory has been developed by Amirtharajah (1984). The backwashing efficiency for air and water wash has been investigated by Regan and Amirtharajah (1984) but all experiments were done using idealised spherical filter grains and microsphere suspensions. The experiments described below use standard filter sand, and clay suspensions.

EXPERIMENTAL TECHNIQUES

A model filter apparatus consisting of a 0.115m diameter, 1m high perspex column has been used for the experiments (Fig. 1). A suspension of kaolin clay (particle size ranging from <1 to ~10 μm) in London tap water (conductivity = 600 μS cm^{-1}, pH = 8, total dissolved solids = 460 mg/l) is supplied to a constant head tank and filtered at a constant rate of 3 m/h through a 62cm deep, partially consolidated, bed of sieved (0.5 - 1.0 mm, d_{60} = 0.77 mm) standard filter sand. When the filter bed is clogged with an average deposit of 5kg/m^2 the flow is turned off and the bed allowed to drain down until the water level is 30 cm above the top of the sand. Head loss through the sand bed is measured at the beginning and end of filtration.

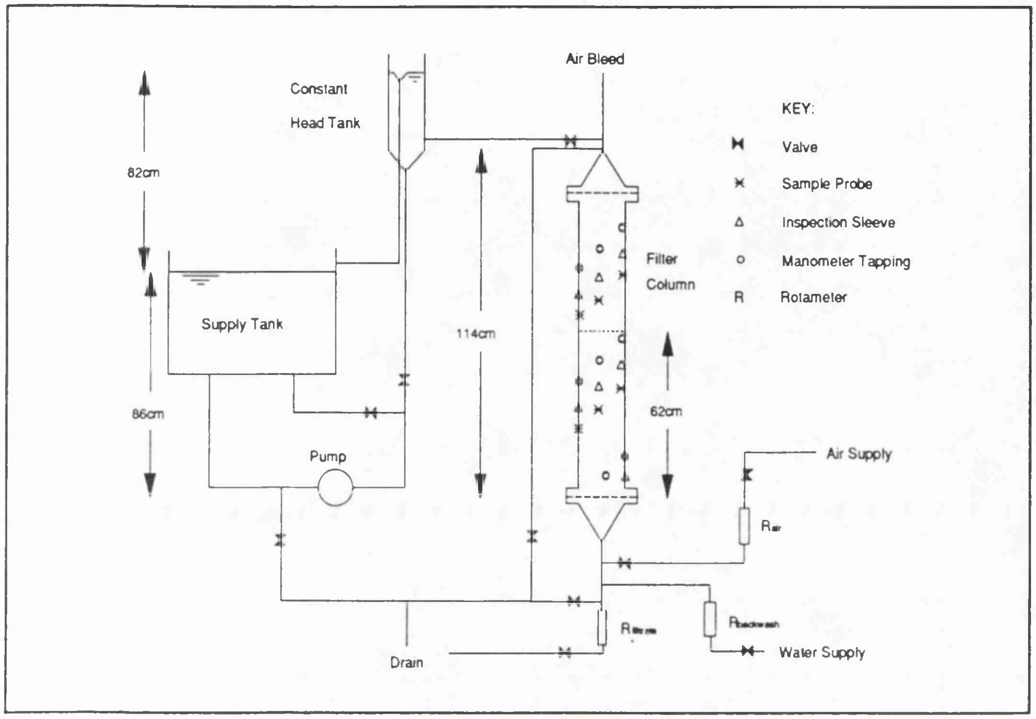


Fig. 1. Schematic diagram of the experimental filter system.

Backwashing takes place and the process is recorded on video tape by means of a rigid optical fibre endoscope (borescope) which views inside the sand bed, through a video camera recording at 200 frames per second (Fig. 2). Illumination of the inside of the filter bed is provided by a light from a 250W mercury arc lamp which is transmitted via optical fibres to the borescope tip. The borescope views the sand bed through a plane glass window with a 1mm grid etched onto it. This technique has been described by Ives and Fitzpatrick (1989) and gives an image with a normal magnification of the order of 100 times. High speed framing is required to freeze the rapid motion of the detaching deposits and the fluidised sand grains. The video equipment is linked via an XY coordinator to a personal computer so that displacement and time measurements may be taken from the video frames, from which velocities, accelerations and shear stresses may be calculated.

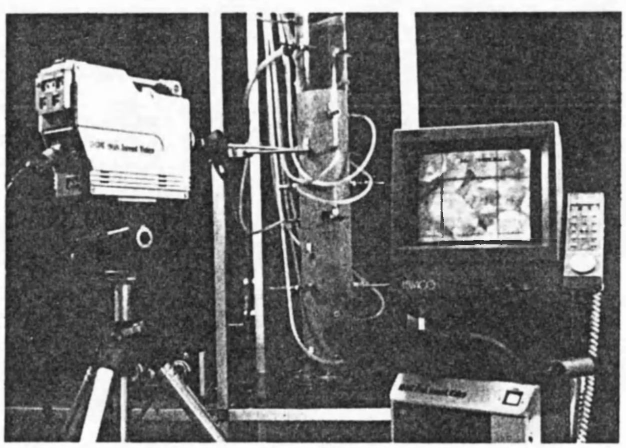


Fig. 2. High speed video camera and recording system mounted on experimental filter column.

Backwash water is collected and samples analysed for average concentration in a given volume for the different backwash water flow rates at different times during the washing process. Additionally, for the experiments conducted using air scour, the backwash water is continuously sampled (at the same depth as the borescope for video observation) using a flow-through turbidimeter, and the analogue signal recorded.

The duration of the water only wash was varied according to the flow rate which continued until the washwater appeared clean. For the air plus water wash experiments, the duration of the air plus water flow is 5 min. followed by a water wash with the bed in the fluidised state for 3 min..

RESULTS

Sub-fluidisation Water Backwash

From the borescope and HSV observations, it appears that significant amounts of deposited kaolin are flushed out without any bed expansion, although there may be slight grain movement as the deposits are detached. As backwash flow starts, even at very low velocities, the top few cm of the bed move as deposits are broken up and dislodged and some slight expansion may occur (< 1cm), the bed then settles to its original height until the flow rate is increased sufficiently so as to cause expansion. For higher velocities, still less than the minimum required for fluidisation of the whole bed, some expansion occurs due to partial fluidisation of the upper, finer sand fractions and grain movement is observed inside the bed.

From the mass balance results from the backwash runs (Table 1) it can be seen that for kaolin of the order of 50% or more of the deposits can be removed for flow rates as low as 7.5 m/h, if the bed is washed for a duration of 12 minutes. Similarly, up to 80% of deposits may be flushed out for flow rates of ~10 m/h after 15 minutes of washing.

Experiment	Length of HSV recording (min.)	Backwash Flow Rate (m/hr)	Time of Wash (s)	% of Deposits Flushed Out
503	8	7.5	228	41
504	7.5	6.9	249	39
505	5	7.7	231 692	36 56
601	12.5	8.9	189 596	53 78
602	14.6	7.6	228 683	36 55
603	6.7	9.6	181 692 1154	49 71.8 72
701	24.5	8.1	215 1080	51 70
702	6.7	8.5	215 1020	53 79
801	6.7	15.0	118 232 692	60 80 97
802	14.6	14.0	135 260 758	62 80 90
803	17.2	11.5	149 301 900	56 77 85
901	5	11.0	157 942	60 96
902	11.7	16.9	103 207 621	60 80 89

Experiment	Length of HSV recording (min.)	Backwash Flow Rate (m/hr)	Time of Wash (s)	% of Deposits Flushed Out
903	10.7	18.5	93 190 545	66 85 93
904	8.3	14.0	125 250 750	53 71 86
905	5	19.6	88 176 529	57 76 87
111	8.3	25.6	67 138 401	58 76 86
112	6.7	26.5	65 128 280	65 81 89
113	6.8	30.6	58 118 339	67 86 86
114	5.9	33.5	51 104 306	69 88 91
115	3.3	39.0	45 133 275	73 90 90
116	5.8	35.3	94 195 294	89 94 95
117	5	40.3	42 86 257	72 89 90

Table 1. Results of experiments from backwashing the experimental filter bed when clogged with kaolin deposits.

Kaolin deposits detaching from the sand grains by fluid shear with a flow rate insufficient to cause grain movement can be seen in Fig. 3.

Fluidised Water Wash

When the clogged bed is backwashed with a water upflow rate sufficient for fluidisation of the sand grains, mass balance results (table 1) show that ~90% of deposits may be removed at flow rates around the minimum fluidising velocity (v_{mf}), which is 23 m/h for the sand used, or greater, if the bed is washed for 9 minutes.

Borescope and HSV observations reveal that many deposits are detached while the valves are being opened, and the flow is reaching its prescribed rate, as the bed gradually becomes mobile and expands. During the partially fluidised phase, which lasts a few seconds, while grains are mobile, grains rotate and move relative to each other which may result in abrasion. When the bed is fully fluidised, grain movement is erratic, showing brief temporal and spatial phases of immobility followed by rapid movement and circulatory motion. Clouds of re-suspended detached deposits continuously flow past the end of the borescope restricting observation of grain behaviour and making particle tracking difficult.

In the fluidised state the sand grains appear to collide but may only approach very closely, protected by a thin fluid film. Grain to grain contact is evident in immobile periods and may result in local abrasion which is insignificant in relation to fluid shear forces. This abrasion does not cause wear of the relatively soft perspex filter column.

The results for the sub-fluidised and fluidised water wash are displayed graphically in fig. 4. A surface has been fitted to the experimental data which exhibits some scatter. From the three dimensional plot it may be possible to select a required backwashing efficiency and then find the optimum combination of velocity and duration of wash for design purposes, depending on whether least cost, least energy or least water is the main criterion.

Air and Water Wash

For combined air and water wash, with water flow less than v_{mf}, followed by a water wash (at greater than v_{mf}) results obtained from experimental measurements indicate an maximum removal efficiency at air and water flow rate combinations satisfying the collapse-pulsing condition. These results are displayed graphically in fig. 5. The maximum efficiency, in terms of deposits washed out is similar to that obtained for water only wash, i.e. ~90% solids removal and a comparable water volume is used. It may be possible to reduce the volume of water used in the subsequent water wash by either reducing the flow rate or the duration.

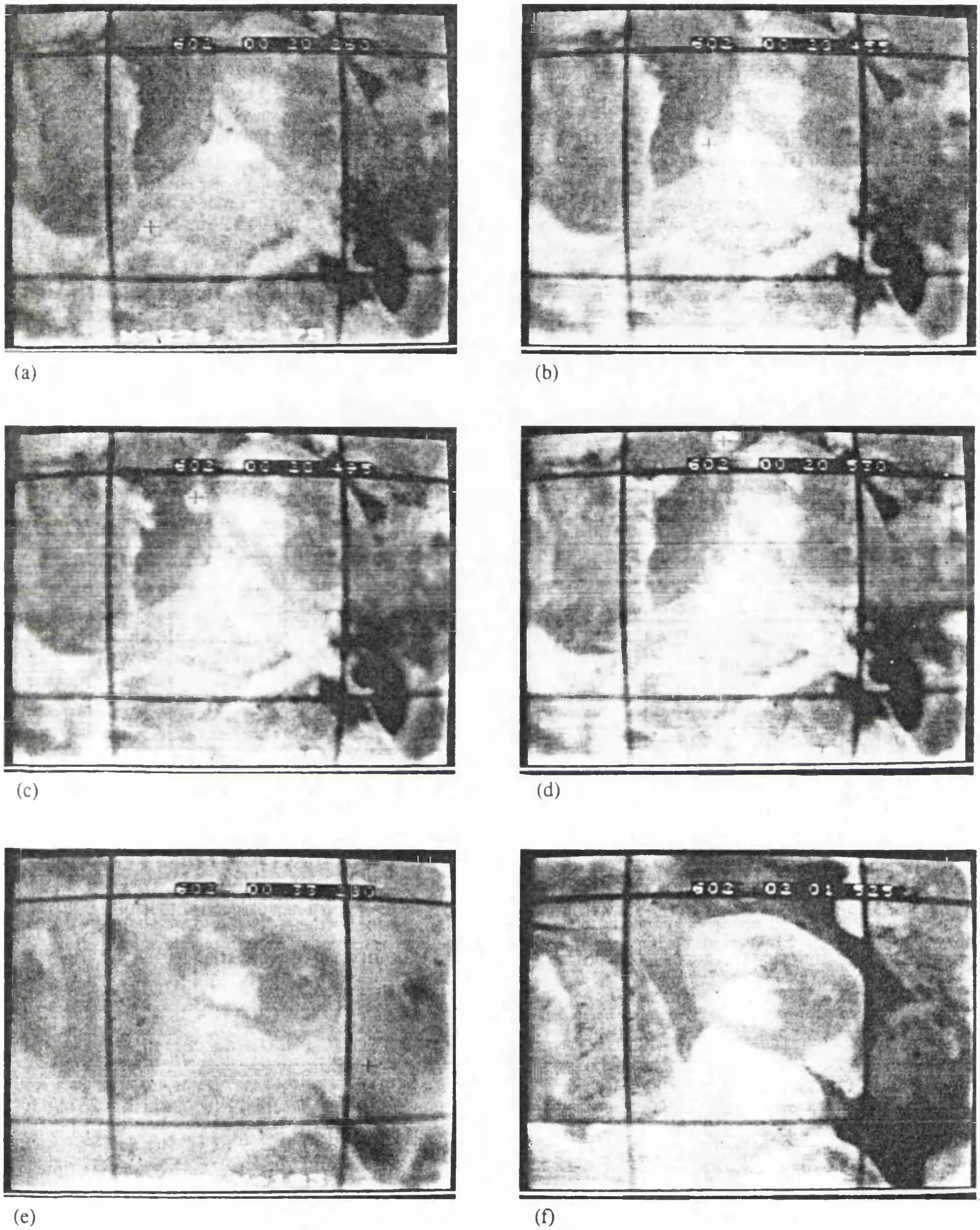


Fig 3. Successive video frames taken from a HSV recording of sub-fluidised filter backwashing (flow rate = 7.5 m/h). The grid is a 1mm square and time, in seconds and milliseconds, is displayed at the top of the frame. Frames (a) to (d) show the movement of a floc detached by fluid shear at the start of backwash. The floc is marked by the cursor (+), whose coordinates can be seen at the bottom of each frame; it has moved ~1 mm in ~0.3s. Frame (e) shows the state of the bed after ~13 seconds of washing; some grain movement has occurred due to particles detaching. Frame (f) shows the bed after 3 minutes of wash; a lot of deposits have been removed but some remain trapped by the static grains.

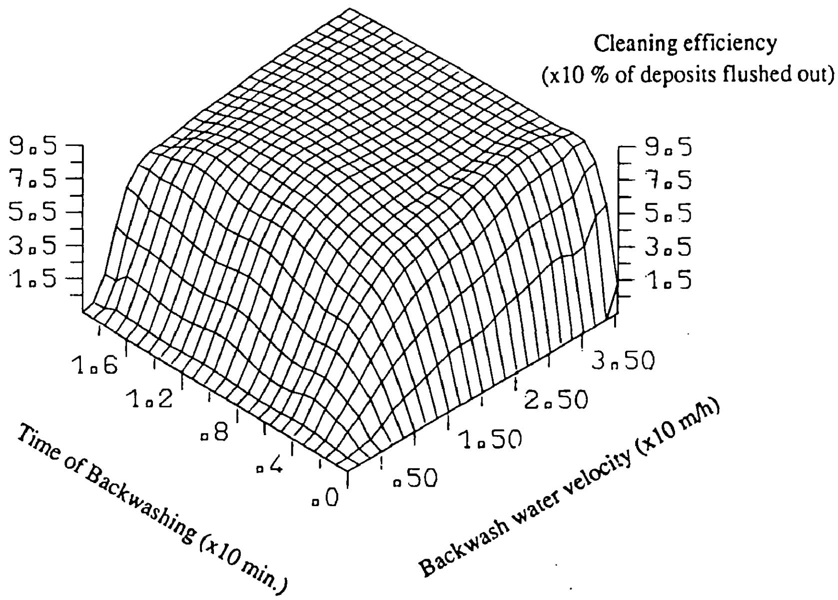


Fig. 4. Surface plot of backwash velocity vs time vs efficiency. Derived from experimental data and smoothed.

It is possible to observe air scour with the borescope and HSV (fig. 6) which show that there is very rapid grain movement while air scour is taking place and deposits are detached very readily, firstly by fluid shear forces caused by flow of pore water when displaced by air, and, secondly, there is grain contact and abrasion, especially during collapse-pulsing.

The motion of the grains during simultaneous air and water flow is different from that observed for water fluidisation. The whole bed pulsates and grain movement is much more violent with rapid changes in the magnitude and direction of grain velocity.

After 5 minutes of simultaneous air and water flow, the grains appear clean and the subsequent fluidising water wash serves to flush out the remaining dislodged deposits from within the bed.

DISCUSSION

The experiments conducted using water wash only have shown that a considerable amount of kaolin deposits, which are not very adhesive, can be removed by fluid shear alone, since when the bed is fluidised there are no collisions, and, in the sub-fluidised state, where no grain movement takes place, large amounts of deposit are removed. When the bed is in a partially fluidised state, there may be some abrasion between grains as they exhibit a grinding motion which may contribute to detachment while the bed is expanding. The bed passes through this phase as flow is increasing for fluidised washing.

These observations of fluid shear detachment of deposits cast doubt on Huang and Basagoiti's (1989) model which assumes that no detachment takes place until the bed is fluidised.

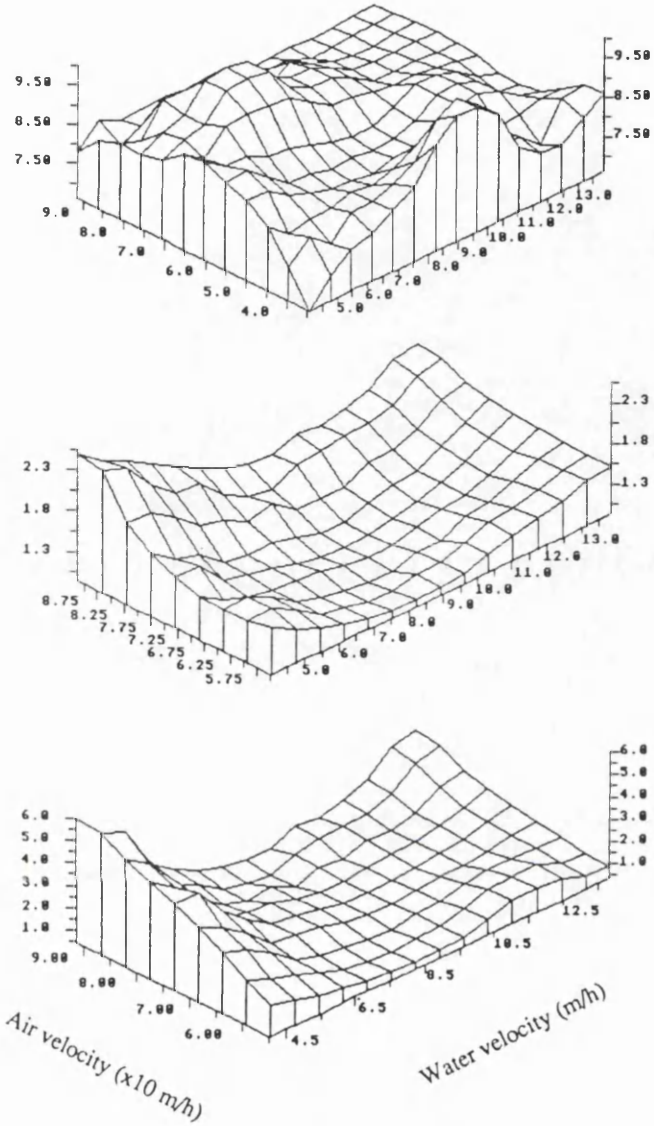
It was not possible with the experimental set-up to test Amirtharajah's (1978) theory of maximum efficiency at 40-50% expansion.

The value for shear stress obtained by Ives and Fitzpatrick (1989) for sub-fluidised washing assumes a porosity, ε, of 0.3. It is possible that in the top few cm of the bed $\varepsilon = 0.15$, which would double the shear stress value to $\tau = 0.54$ Nm^{-2}, since $\tau \alpha 1/\varepsilon$. But, this value for shear stress is an average value, calculated on an assumption of a paraboloid velocity distribution within the pores. It is probable that it is the maximum values of τ which are responsible for detaching deposits. This information may be obtained from future analysis of the video recordings, after taking velocity measurements.

The subsequent grain movement followed by bed expansion, with increased flow, appears only to expose new faces of the sand grains to the fluid flow, and consequent shear stresses, which carry away the remaining particles. This evidence suggests that for the experiments conducted so far that the dominant detachment mechanism is fluid shear.

When the bed is fluidised the average shear stress on grains increases until it reaches a maximum value, dictated by conditions of turbulence. The shear stress is greater because of the increased drag required to maintain the grains in a fluidised state. But, the range of velocities and hence the shear stresses may be less which may mean lower local maximum shear stresses, which will affect deposit detachment.

During combined air and water wash the sand bed pulsates giving local grain velocities as high as those observed in a fully fluidised bed, but this is achieved with much lower water rates (~20 - 45 % v_{mf}). These rapidly changing velocities would give rise to high fluid



(a)
Cleaning efficiency (x10 %) for different air and water rates

(b)
Time (x100 s) for turbidity to reach < 2000 NTU

(c)
Turbidity (x100 NTU) at end of air/water wash

Fig. 5. Surface plots of results from combined air and water wash experiments with a kaolin clogged bed.

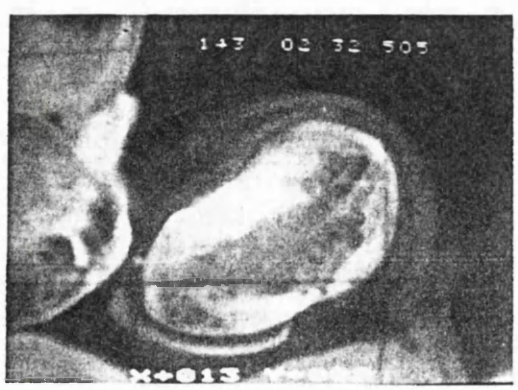


Fig. 6. Video (HSV) image of air passing the borescope tip during air plus water wash.

shear stresses on the grains and attached deposits, in addition to the stresses from abrasion and grain collisions when the sand collapses into the wake of passing air bubbles. Additionally, there may be shear stresses on grain surfaces due to surface tension of a moving water film at the air water interface of a passing air bubble, which can be observed on the video recordings.

Simultaneous air and water wash may maximise detachment because it maximises fluid shear and grain collisions when in the collapse - pulsing state. Subsequent water wash is required to flush out the detached deposits from within the bed. The total washwater volume can be minimised by finding the minimum duration and flow rates required for this flushing process. It is important to fluidise the bed with water after air has been used in order to re-stratify mixed media and remove any air trapped within the sand. Since fluidisation is required for this purpose, more water may be required for the same cleaning efficiency as may be achieved with a partially fluidised water wash which will not mix media or trap air.

CONCLUSIONS

1. Using the borescope and high speed video set up it is possible to observe the filter backwashing process when washed with water only, and also when air scour is introduced.

2. Collected and analysed backwash water gives information about the efficiency of the wash in terms of quantity of deposits removed.

3. It has been observed that the clogged bed behaves differently from a clean bed during backwash. Grain movement occurs in the top layer of a clogged bed for flows as low as 8m/h, whereas in the clean bed a flow rate of 17 m/h is required. The top layer of the clogged bed expands and then resettles due to higher velocities in the restricted pore space.

4. For subfluidised washing with water only, up to ~90% of deposits are removed from a sand bed clogged with kaolin clay if washed for a minimum of 9 minutes. The majority of these deposits are detached by fluid shear, but for higher wash rates abrasion between mobile grains, due to partial fluidisation, may enhance the process. Alternatively, movement of the grains may serve to expose new deposits to the shearing effect of fluid flow.

5. When the bed is fully fluidised, results for a kaolin clogged bed show that there is no significant increase in removal efficiency from that measured for the subfluidised state for expansions up to 15% (40 m/h upflow).

6. For combined air and water wash, followed by bed fluidisation with water only, optimum cleaning occurs at flow rates satisfying the collapse-pulsing condition predicted by Amirtharajah (1984). Greater than 90% removal efficiency of kaolin clay may be obtained. Removal is principally by fluid shear enhanced by abrasion between grains during collapse-pulsing.

7. Experiments have begun using kaolin flocculated with alum to clog the bed and further experiments will be done with kaolin flocculated with alum and polymer to see how readily these more adhesive deposits are detached by the various washing techniques.

NOMENCLATURE

τ	Shear stress, Nm^{-2}
ε	Porosity of sand bed
v_{mf}	Minimum fluidisation velocity, m/h

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REFERENCES

Amirtharajah, A. (1984). Fundamentals and Theory of Air Scour. *Journal of the Environmental Engineering Division, A.S.C.E.*, 110, No. 3, 573-590.

Amirtharajah, A. (1978). Optimum Backwashing of Sand Filters. *Journal of the Environmental Engineering Division, A.S.C.E.*, 104, 917-932.

Dharmarajah, A. H. and Cleasby, J. L. (1986). Predicting the expansion behaviour of filter media. *Journal of the American Water Works Assoc.*, 78, 66-76.

Hewitt, S. R. and Amirtharajah, A. (1984). Air Dynamics through Filter Media during Air Scour. *Journal of the Environmental Engineering Division, A.S.C.E.*, 110, No. 3, 591-606

Huang, J. Y. C. and Basagoiti, J. (1989). Effect of solids property on rates of solids dislodgment. *Journal of the Environmental Engineering Division, A.S.C.E.*, 115, No. 1., 3-19.

Ives, K. J. and Fitzpatrick, C. S. B. (1989). Detachment of deposits from sand grains. *Colloids and Surfaces*, 39, 239-253.

Moll, H. G. (1986). Expansion of Filter Media during Backwashing. *4th World Filtration Congress. K.VIV*, 1986 (1), 8.13-8.21.

Quaye, B. A. (1987). Predicting optimum backwash rates and expansion of multi-media filters. *Water Research*, 21, No. 9, 1077-1087.

Regan, M. M. and Amirtharajah, A., (1984). Optimization of Particle Detachment by Collapse-Pulsing during Air Scour. *Proceedings of Conference of the American Water Works Assoc.*, Dallas, Texas, June 1984 (16pp).

Sholj, I. (1987). Expansion of Granular Filters during Backwashing. *Journal of Environmental Engineering, A.S.C.E.*, 113, No. 3, 516-531.

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THE MECHANISMS OF DEPOSIT DETACHMENT DURING FILTER BACKWASHING

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During the process of deep bed (gravity) filtration at the water treatment works, suspended particles in the water are deposited on grains within a filter bed. Periodically the filter requires cleaning, involving the upward flow of water with, or without, upward air flow (scour).

The technique of video endoscopy has been used to study backwashing of filters using a high speed video camera operating at 200 frames/s. This has enabled very rapid movements of sand grains, and detaching deposits, to be observed and recorded for examination in slow motion and freeze frame. Using an XY coordinator, coupled to a PC, velocity measurements have been made under various experimental conditions. Experiments utilised kaolin, and kaolin flocculated with alum and a cationic polymer as suspensions which clogged a 620 mm deep experimental sand bed (0.5-1.0 mm) with approximately 5 kg/m^2. The borescope (rigid endoscope) penetrated into the sand bed ~70mm below the sand surface.

Experiments with clean sand showed some grain movement at ~0.75 minimum fluidisation velocity (v_{mf}), intense rotational and translational movement at v_{mf}, and very rapid movement at 1.25v_{mf} (4.5% expansion). The clogged bed backwashed with water only, gave a relationship between wash velocity and duration, and the percentage of deposits removed. This showed that up to 80% could be removed at 0.5v_{mf} after 15 min, and ~90% at v_{mf} for 9 min. Deposits were observed detaching from grains, due to fluid shear forces, as soon as flow reversal commences. Movement of the grains as the bed becomes fluidised exposes new surfaces to the shearing effect of the flow and aids flushing out of detached deposits.

For experiments utilising combined air and water, air bubbles were observed through the borescope, and at critical combinations of air and water rates intermittent violent agitation of the bed occurred (Amirtharajah's collapse-pulsing). At collapse-pulsing there was a maximum removal efficiency mainly by fluid shear forces. Analysis of grain movements showed that higher velocities occurred during collapse-pulsing which were equivalent to those obtained in a fluidised bed but with <50% of the water flow. Subsequent water backwash for 3 min at 1-2v_{mf} is required to flush out remaining dislodged deposits and trapped air.

These laboratory results indicate that the dominant detachment mechanism is fluid shear, whether, or not, the bed is in a fluidised state. Detachment can be enhanced by grain collisions and abrasion, particularly when air scour is used, for removal of more adhesive deposits.

DISCUSSION

G.C. JEFFREY (BP Research International, Sunbury, United Kingdom)

The endoscope allows the bed to be viewed in the vicinity of the probe. Is the probe likely to introduce effects similar to wall effects?

K.J. IVES

The effect of the probe is to create an atypical void below the cylindrical barrel. Viewing is beyond the tip and therefore, hopefully, beyond such disturbance. The "window" at the endoscope tip is 8 mm diameter, which is considerably less than the wall area. Therefore it is assumed that any wall effect is very much less, in such a restricted area.

L.H. LITTLE (University of Western Australia)

(1) Is the relative inactivity at the side due to an edge effect or is it a function of the position of the jets on the bottom?

(2) What would happen if the pressure was cycled between the operating pressure and zero, instead of maintaining a steady flow?

K.J. IVES

(1) The bottom of the filter column, which supports the sand, is a metal gauze, without jets, distributing the washwater uniformly. There the lack of movement of particles on the sand surface, next to the wall, is attributed to a wall effect.

(2) Pulsation washing would be very effective in cleaning the sand, due to water accelerations. This would introduce an extra technical requirement in practical systems. Air bubbling (scour) produces a similar effect in practice, by a pulsing collapse of the sand into the spaces behind the rising bubbles.

J.E. TOBIASON (University of Massachusetts, Amherst, MA, USA

What is the particle size resolution of the video apparatus?

K.J. IVES

On a large monitor screen it is possible to obtain about 500× magnification, with a resolution of 15–20 μm. Smaller particles of kaolin, being plate-like, and rotating in the flow, are sometimes seen by scattered light.