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Filtration by falling particles

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Abstract

In one variation of deep-bed filtration the liquid is passed *upwards* through a fluidized bed of particles. In this variation, filtration efficiency is very much dependent on some type of attraction between the bed particles and the suspended particles, otherwise the suspended particles flow easily through the much larger voids in the fluidized bed, and filtration efficiency is low. When this inter-particle attraction exists, another variation in filtration procedure is possible. This is to pass the fluidized bed *downwards,* by gravity, through the liquid to be filtered. This variation is the subject of this paper. The ability of falling particles to induce a *flow pattern* in the body of the liquid makes it possible to devise a very large scale continuous filtration operation, to clarify volumes too large for other filtration techniques, especially when the suspended solids are at a very low concentration. In all of the above, the word *gas* can be substituted for the word *liquid,* and the whole spectra of gas cleaning by falling liquid or solid particles opens up. One of these — the cleaning of dust from the atmosphere by falling raindrops — is a familiar and interesting example of simultaneous filtration and flow inducement. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The use of a stationary fluidized bed, to remove fine particles from a fluid flowing upwards through it, is a well established technique. It is used extensively in sewage treatment plants [1] where because of the volume of liquid to be treated it is the only economic separation process available. One specialized process for sewage plant effluent clarification [2], and also applicable to potable water [3] uses upwards flow through a bed of flocculated magnetite particles.

Upwards flow is also used in chemical industry in applications where particularly large volumes of liquid have to be clarified. An example can be found in some of the plants in the alumina production industry, where very large volumes of caustic alumina solutions have to be freed of traces of 'red mud' before the precipitation of pure alumina can begin.

There is one factor which these, and other similar applications, have in common. This factor is that the solid particles to be removed are extremely small in relation to the mean void diameters in the fluidised bed. This means that the particles are not trapped by being too large to pass through the voids (as happens with surface filtration). They are trapped by some sort of attraction between the particles and the solids of the filter medium.

To utilize this technique of filtration, it is usual to keep the filter medium essentially stationary, by arranging the liquid flow so that the upwards friction it applies to the filter bed is equal to the downwards gravitational force of the bed. If filtration is achieved in this way, there is no reason why similar filtration cannot be achieved by keeping the fluid stationary, and allowing the bed to drop through the static liquid at whatever rate gravitational force will determine. The relative motion between liquid and solid is not changed. This variation is the subject of this paper.

It is important to differentiate between falling-bed filtration of a liquid, and the widely used clarification of a liquid by mixing flocculant and/or flocculated particles with the entire volume of the liquid and then separating the two phases by sedimentation. In the latter operation the flocs are made to fall through the liquid merely to separate them from the liquid. In the former, the fall provides the means by which the flocs are brought into intimate contact with the suspended solids, thereby eliminating the need to agitate the entire liquid volume.

2. Applications

There would seem to be possible advantages in using the falling bed clarification technique where certain conditions make upwards flow through a static bed uneconomic, or, at worst, impossible. The most important of these conditions is that if the turbid liquid to be clarified is water, and is part of a large body of water such as a harbour, river, lake or pond. In such cases it is obvious that if the water is pumped

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away to a vessel containing a static fluidized bed, and back to where it came from, mixing of the filtrate with the filter feed cannot be avoided. Furthermore, there is the problem of intimately mixing the flocculated solid with the entire turbid liquid volume.

A second condition is that the solids concentration of the particulate solids causing the turbidity is very low, and the particles are so fine that they would blind a conventional filter (even if it is possible to pump the liquid to a filter). Solids of such low concentration and small size, are very difficult to remove by the alternative of sedimentation. Simply mixing a flocculant into such suspensions is usually ineffective because there is insufficient mass of solids to create large, fast settling, flocs.

Another large scale application can be envisaged where sand filters are used to clarify very large volumes of turbid water (e.g. in the production of potable water from river water). Any economical pre-treatment of the feed to the filters can minimize costs by lengthening the filtration cycle time. This has already been claimed as a major advantage of the use of the Sirofloc® process [4]. Though this process does not normally utilize a falling bed, (in fact an upwards flow rate of 18 m h^{-1} through a stationary bed is mentioned) there would appear to be no reason why a falling bed could not be used.

A further large scale application could be for the clarification of water in resevoirs, lakes, ponds, harbours etc. In these bodies of water, clarification is needed to facilitate underwater excavation, exploration of wrecks and other sunken objects, and the search for leaks. In these cases the avoidance of re-suspension of already settled particulate matter can beat least as important as the clarification of the liquid body. Experimental work has shown that flocculated solids settled to the bottom can be re-suspended by agitation, but they settle again so rapidly that the re-suspension causes no lasting turbidity.

3. Flowsheet

As with most separation operations, falling bed filtration can be arranged as:

1. Continuous;
2. Semi-continuous (a sequence of batch operations); or
3. Batch

All of these alternatives can be represented by a flowsheet as shown in Fig. 1. In each case a suspension of the filter medium solid has to be distributed as evenly as possible to the surface of the turbid liquid. It then falls by gravity through the turbid liquid, where by some sort of attraction the large falling particles absorb the fine suspended particles and carry them to the bottom. At the bottom there has to be a means of concentrating the filter medium so that it can be returned to the top for the next cycle.

It is easy to see how this operation can be carried out batchwise. The vessel is filled with the turbid liquid, followed by recirculation of the filter media for sufficient time to reach the desired clarity. The recirculation is then stopped, and the vessel is left undisturbed until all the filter medium has settled. The clarified liquid is then drawn off (through a side outlet), and the vessel is refilled with the next batch of turbid liquid. As the mass of the filter medium will increase with each batch, either continuous or intermittent disposal of a small part of the filter medium has to be arranged. If the composition of the filter medium is different from that of the suspended solids in the turbid liquid, intermittent addition of filter medium is necessary, otherwise its composition will gradually approach that of the suspended solids.

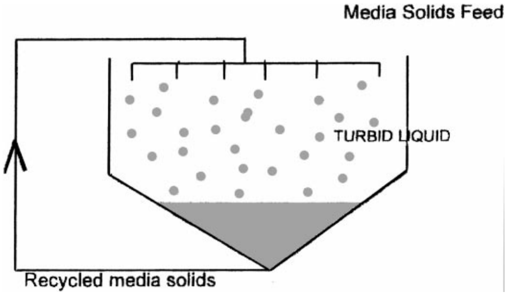


Fig. 1. Clarification by falling filter bed — schematic.

For a continuous operation, the media circulation is made continuous, and there are continuous feed and product streams. Some means, such as a settling chamber, has to be provided to prevent filter media particles from contaminating the product stream. A general arrangement is as shown in Fig. 2.

3.1. The need for flocculation

It will be obvious that the throughput of a falling media clarification operation will be too low to be useful unless the falling solid particles have a high settling rate. Though solid particles with a large mesh size can be expected to fall at an adequate rate, their surface areas are bound to be too low to adsorb much of the fine particles suspended in the turbid liquid. Fine mesh particles have a larger area/mass ratio, but settle too slowly.

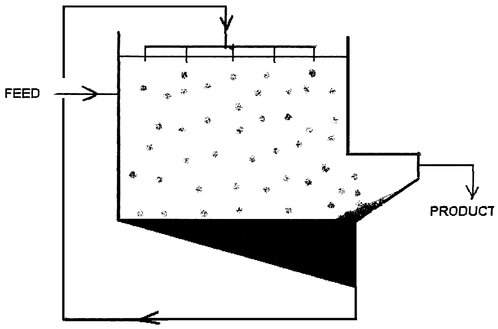


Fig. 2. Falling bed clarification — continuous.

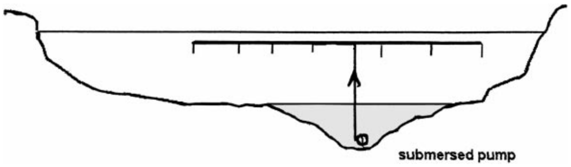


Fig. 3. Clarification of a large body of water.

The solution to this problem is to use extremely fine particles and flocculate them so that they form large, rapid settling, particles with a very high area/mass ratio. Fortunately, there is now a very wide range flocculants available, at affordable prices, so that it is possible and economic to flocculate almost any fine particulate solid.

Flocculation of the filter media solids opens up the possibility, in some cases, of using the suspended solids in a turbid liquid as the material for a filter medium for its own removal. For example, the silt causing the turbidity in a large volume of water will have the same composition as the silt already settled (naturally) to the bottom. If this sediment is pumped up and flocculated, it can provide the filter medium for silt removal from the water body. See Fig. 3.

3.2. Flocculant consumption

Experimental work carried out so far has shown that the consumption of a very high molecular weight flocculant of the polyacrylamide or polyacrylamide/acrylate co-polymer type can be very low in this application. Typical flocculant demands have been 2–4 ppm, based on the liquid weight, and the consumption appears to be independent of the solids concentration, at least at the concentrations likely to be encountered in this type of clarification. This consumption scales up to 2–4 g of solid flocculant per cubic metre of water. Assuming a flocculant cost of around $US 4 per kilo, the cost of clarifying a cubic metre of water would be between 8 and 16 cents. The main factor affecting cost is likely to be the extent of floc breakdown during recirculation, as this will determine the top-up need.

3.3. Residual flocculant in the product

As with other solid/liquid separation operations which use flocculation of the solid to make the operation economical, the falling bed technique is limited to applications where a trace of flocculant in the clarified liquid is not objectionable.

Though polyacrylamide and polyacrylate flocculants are non-toxic at low concentrations, (and have, in fact, been approved by the FDA in the USA for use in the clarification of potable water) any future higher-efficiency flocculants would have to be screened for toxicity. While 2–4 ppm might be used to achieve satisfactory flocculation, it should be remembered that the concentration in the product clarified liquid would be very much lower than this. Flocculants partition between the solid surface and the liquid, with the major part going to the former, due to their strong adsorption on surfaces. In most applications the residual concentration is likely to be much less than 1 ppm. However, each application should be subject to a laboratory determination of the residual flocculant concentration.

3.4. Practical considerations

Figs. 1–3 are merely schematic representations of possible applications of the falling bed method of liquid clarification. In practice, there are engineering challenges in carrying out this technique, but there is no reason to believe that these are impossible impediments.

Foremost, there is the problem of distributing the flocculated filter medium evenly at the surface of the liquid body so that it will fall as a uniform cloud through the turbid liquid. This requirement will obviously increase in difficulty as the volume and area of the liquid increases. If the liquid is contained in a vessel or tank between 2 and 20 m in diameter, there is little difficulty in arranging an array of perforated pipes to distribute the filter medium. When the area is much larger than this, (as would be case in a lake, for example) a fixed array of feed pipes becomes less practical, and some sort of distributor which traverses the surface may become a more economic alternative.

The equipment used to pump the settled media to the surface also presents an engineering challenge. Experimental work has shown that high-turbulence pumps, such as high speed centrifugals, are capable of breaking the floc structure of the settled media, so that it will settle at progressively slower rates with each pass through the system. Though experimental work has shown that floc size can be recovered by a ‘topping up’ addition of flocculant at the return flow to the surface, it has also been shown that the amount of flocculant required to do this increases in proportion to the turbulence used in pumping. Fortunately, the head required to return the media to the surface would be low in all applications. This means that in the use of low-head, high capacity, low turbulence pumps lies the opportunity to economize on the use of flocculant and pumping power, thereby improving the economy of the operation.

The formation of channels in the falling bed could present a problem to be overcome by proper design. Whereas channel formation is known to be essential for efficient de-watering of compacting dense beds of solids, channels in a fluidized bed (either stationary or falling) results in a high proportion of the liquid by-passing most of the filtration medium.

In all applications, it is imperative, from the economic standpoint, that the filter medium be recycled. This means that it has to sediment to a point from which it can be pumped back to the surface. In a relatively small application this is no great problem, as it is necessary only to fit a conical bottom to the vessel so that a pump connected to the apex of this (inverted) cone can return it to the surface. Larger applications (such as a lake) also need one or more deep points to act as collection points to feed the suctions of one or more recirculation pumps. In some cases, these deep points may be naturally occurring, whereas in other cases they may have to be provided by dredging.

3.5. The role of particle density

Obviously, the settling rate of flocs will depend not only on the size and shape of the flocs, but also on the density of the solid particles forming the flocs.

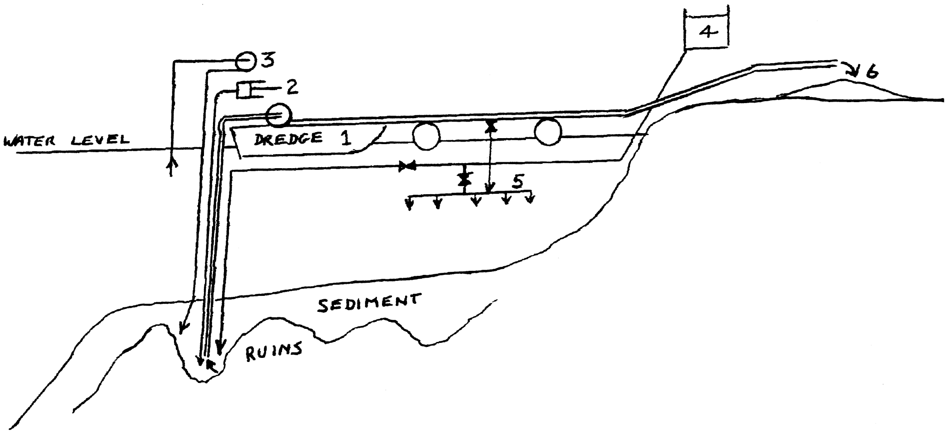
Unfortunately, the particles causing turbidity in a body of liquid are often of organic origin (e.g. sewage solids or fine particles from rotting vegetation) and these naturally form flocs of density very little greater than that of the suspending liquid. To achieve a satisfactory settling rate it may be necessary to add a higher density ingredient, such as fine inorganic silt. This material will recirculate with the flocculated low-density material, but make-up additions will have to be made either intermittently or continuously to maintain the desired floc density.

If the economics of the process justify it, i.e. if the water or other liquid to be clarified is of sufficient value, a very dense solid can be incorporated into the flocs, to induce a correspondingly high settling rate. Thus, in the Sirofloc® process, already mentioned, finely divided magnetite (S.G. 5.1) is the major solid component of the flocs [5]. Besides imparting a high settling rate (or high upflow rate if a stationary fluidized bed is being used) the magnetite can be magnetically separated from the clarified liquid, instead of being sedimented.

3.6. An interesting application

An intriguing possible future application of falling bed filtration, is the one which gave rise to this study. It is the need for clarification of turbid seawater overlying the sunken ancient city of Port Royal, Jamaica. This large and wealthy city sank in a disastrous earthquake in 1692 [6]. Exploration of the remains (and recovery of very valuable artifacts) has always been hampered by poor visibility in the water overlying the area. Not only is the water always turbid, but the solids which have settled over the past three hundred years are easily re-suspended by any activity in the area, making the water even more turbid. Divers have always complained of having to work in almost complete darkness, with near zero visibility.

There exists by now sufficient tonnage of settled solids (organic plus inorganic silt) to supply all the filter medium needed for clarification of the water for short or long periods, as required. Fig. 4 shows a rough schematic of the concept. A suction dredge would continuously remove a slurry of already settled solids from the area. Part of this flow would be flocculated and returned to the area of water to be clarified i.e. the area undergoing exploration. Surplus settled solids would be removed as necessary by suction hoses. Fortunately this area experiences only very slight tidal variations and currents, so once the water has been clarified it will remain so for a reasonable period of time.



Key:

1. **Dredge**
2. **Air Compressor**
3. **High pressure water pump**
4. **Flocculant preparation tank.**
5. **Flocculated sediment distribution pipe.**
6. **Sediment disposal.**

Fig. 4. Proposed arrangement for clarification of the water over the sunken city of Port Royal, Jamaica.

4. Experimental work

Results of most of the experimental work done so far on the clarification of liquid by falling particles have been visual, and have been recorded by still photography and/or videotape. However, Fig. 6 is a graph of numerical results obtained by the use of a ‘measuring cylinder turbidimeter’, a diagram of which is shown in Fig. 5. This turbidimeter can be adjusted (by the zero adjust potentiometer) to give readings from zero (opaque) to 100 (clean water transmittance) of the contents of a standard 500 ml measuring cylinder. The light source and detector assembly can be adjusted to any desired height on the cylinder, and the cylinder can be inverted to re-suspend settled solids without disconnecting the power (12 V) and output (mV) leads.

The graph of Fig. 6 shows numerically the phenomenon that has been observed many times before, which is that the liquid clarity improves with each fall of the flocculated solid through it.

The right hand curve represents the clarification rate of a low solids concentration slurry without any flocculation. It is so slow that a logarithmic time scale has had to be used to get it on to the same graph as the other curves.

The middle three curves show the effect of flocculating the settled sediment with 5 ppm (based on the total liquid weight) and suspending it in the turbid supernatant (by inversion of the cylinder). The curves 5 ppm (1), (2), and (3) represent clarification rates after 1, 2, and 3 inversions followed by sedimentation, without any extra addition of flocculant. It can be seen that each re-suspension improves the final clarity, the greatest improvement being between the first and second re-suspension.

The left hand curve shows the effect of addition of a further 5 ppm of flocculant (bringing the total to 10 ppm) after the third sedimentation (5 ppm×3) and re-suspension.

This additional flocculant dramatically increased the clarification rate so that almost 100% transmittance was reached in 10 s. The flocs were very large and settled to the bottom in less than 10 s. There was no point in re-suspending this time, as there was no improvement to be made.

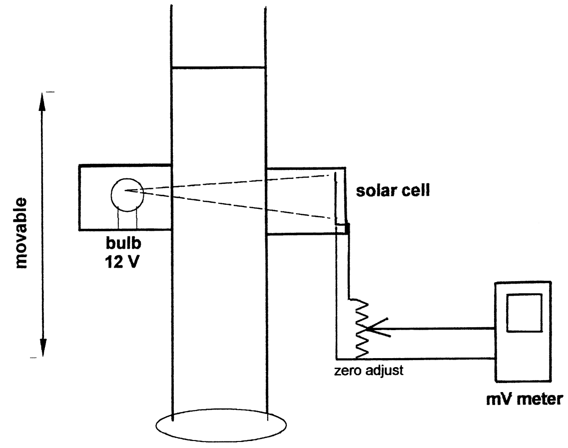


Fig. 5. Measuring cylinder turbidimeter.

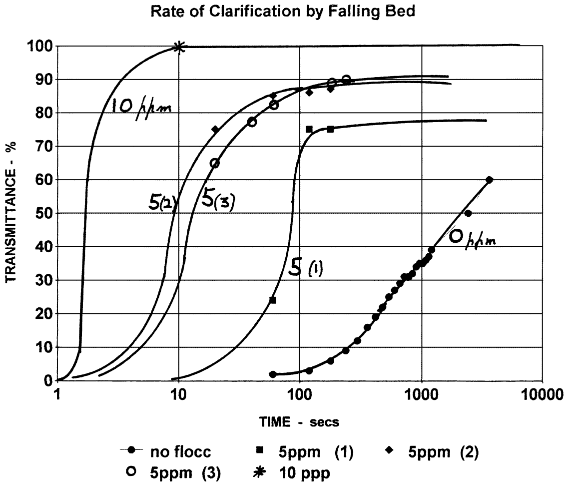


Fig. 6. Rate of clarification by a falling bed.

5. Unknowns

Fig. 6 shows results which are typical for a range of solid compositions and several flocculants of the polyacrylamide/polyacrylate type, for clarification of both fresh water and sea water. Some of the questions which remain to be answered by further experimental work are:

1. How does the rate and completeness of clarification depend on the solids concentration in the falling bed?
2. How does pH variation affect the efficiency of clarification?
3. Should the flocculant be fed to the turbid liquid, or to the filter medium slurry before the two are brought into contact?
4. From the wide range of flocculants available, which is optimum (efficiency and costwise) for a particular application?
5. How does the consumption of ‘top-up’ flocculant depend on the method of recirculating the filter medium from the bottom of the liquid body to the top?

6. Comparison with other systems

What has been considered so far is the effect of solid particles (fine and flocculated) falling in a liquid. This represents just one example within the overall phenomena of particles falling by gravity in fluids. Another example of this phenomena is to be found in the fall of liquid particles (drops) in a gas (usually air). Two major cases of this are to be found in:

1. Gas scrubbing in process plants; and
2. Rainfall.

Both of these achieve clarification of the fluid medium. In scrubbing, clarification is the purpose, but this is the only factor in common with the clarification of a liquid by a falling fluidized bed of solids. Obviously, there is no flocculation, the fluid is not static, and the scrubbing liquid is usually injected under pressure. Clarification probably occurs mainly by collision between drops and particles, with adsorption playing a minor role, if at all.

In the case of rainfall, clarification of the atmosphere appears to occur, but whether this is due mainly to collision between raindrops and suspended dust particles is in doubt. Apparent clarification could also be due to air at ground level being replaced by cleaner air from the upper atmosphere; a mechanism which implies the existence of vertical airflows and has important implications in the design of equipment for liquid clarification.

7. Vertical fluid flow due to falling particles

As is well known in chemical engineering, the fall of any particle in a fluid is resisted by a frictional force due to the viscosity of the fluid. For spherical particles, falling in air, the friction force experienced by each particle is given by the equation:

$$F_{\mathrm{d}} = \frac{C A_{\mathrm{p}} u^2 \rho}{2 g_{\mathrm{c}}}$$

where C is the drag coefficient; A_{p}, the projected area of particle (in direction of movement); u, the velocity of a particle, relative to the air; ρ, the density of air; and g_{c}, the gravitational constant.

When falling from rest ($u = 0$) the weight of the particle exceeds the frictional force and the particle accelerates to its terminal velocity, at which point F_{d} equals the weight. What must be remembered is that the particle exerts an equal force on the air through which it falls, and this will inevitably result in some downwards flow of the air, the magnitude of which will depend on the resistance to this flow.

In a heavy thunderstorm, raindrops can be very large (6 mm diameter, or so) and most of them have been falling long enough to have reached close to terminal velocity. A column of rain weighing x tonnes, will therefore exert a downwards force of nearly x tonnes on the column of air in which it is suspended.

As there is very little resistance to such air flow, the downwards velocity can reach quite high values. Such downflows are known as *downbursts*, and are well known, and feared, by aircraft pilots. Many crashes have been attributed to them. They have also been known to capsize small boats.

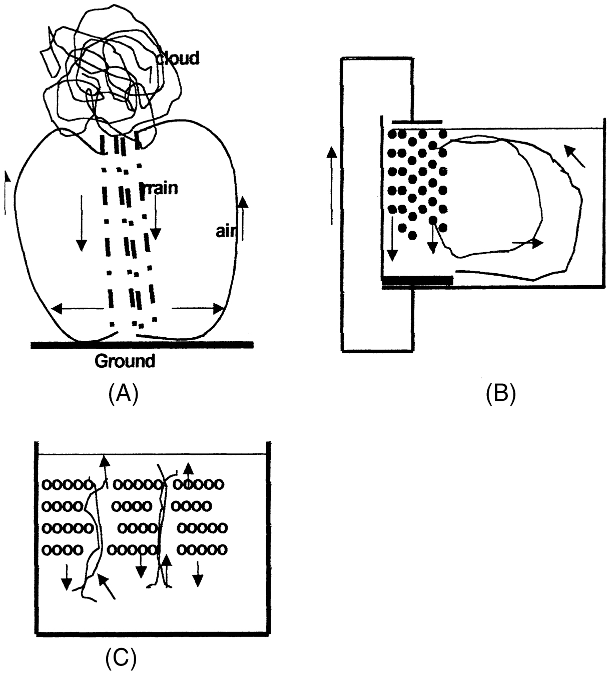
In agriculture, downbursts have destroyed crops, due, apparently, to the effect they have on the velocity (and therefore on the kinetic energy) of raindrops when they hit the soil. In agricultural engineering, it is usually assumed that raindrops cannot reach velocities greater than their calculated terminal velocities. What tends to be forgotten is that terminal velocity equations give the terminal velocity *relative to the air in which they are falling.* If the suspending air is descending at downburst velocity, drops can reach terminal velocity *plus* this downburst velocity.

Reliable data on the magnitude of downburst velocities are sparse, due mainly to the fact that continuous wind velocity recorders are usually positioned to respond only to the horizontal component. Calculations on data obtained from aircraft crashes indicate that velocities of 47 m s^{-1} occur, with the result that raindrops can hit the soil with a velocity of 5 times the calculated terminal velocity, and with a corresponding kinetic energy of 25 times.

8. Vertical fluid flow induced by falling particles — importance to the liquid clarification application

The above paragraph shows that the induction of vertical flow in a gas, due to friction with falling liquid particles, can have disastrous effects, particularly in the fields of aeronautics and agriculture. When the fluid is liquid, and the falling particles are flocs of fine solid particles, induction of vertical flow in the liquid is far less dramatic. This is due, of course, to the much lower height of fall, lower density difference between solid and liquid, and greater inertia of the liquid body. However, liquid flow is inevitably induced by falling flocs, and provision needs to be made for it.

Fig. 7(a) shows how downbust airflow returns with little resistance by routes where there is no rainfall. Fig. 7(b) shows diagramatically how a similar low-resistance return path must be provided where liquid is being clarified by a



(A) (B)

(C)

Fig. 7. Effects of inducement of flow in the fluid phase by falling particles.

falling floc bed in any sort of vessel. If an attempt is made to feed the floc over the entire surface area of the vessel, the return flow will return to the surface by creating channels, as shown in Fig. 7(c). This will reduce efficiency by by-passing, resulting in less satisfactory contact between liquid and flocs.

There are also engineering challenges to be faced in any large scale application that might be contemplated.

9. Conclusions

A variation on filtration by upwards flow of a liquid through a fluidized bed of solids is proposed. In this variation, the bed of solids is made to fall vertically downwards through the liquid.

A limited amount of experimental work has been done to demonstrate the effectiveness of this technique, at least on a small scale. It is a technique which could well be effective in some applications where clarification of a liquid is not possible by any of the conventional solid/liquid separation methods.

A great deal of experimental work is needed to assess the efficiency and economics of the technique in any particular application.

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