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Mechanical Dewatering of Fine Coal and Refuse Slurries

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Die mechanische Entwässerung von Feinkohle und Abfall-Schlämmen

Alternative fest/flüssig Trennverfahren bieten eine breite Palette von Anlagen zur Entwässerung von Feinkohleschlämmen. Die Bedeutung der Auswahl der wirkungsvollsten Kombination von Entwässerungsmethoden wird unterstrichen durch die steigenden Kosten für Energie, die für konventionelle Trocknungsanlagen erforderlich ist. Das Ziel bei der Auswahl bestimmter Fließschemas sollte eine maximale Herabsetzung der Feuchtigkeit und nicht eine maximale Klärung der Abfallwasser sein (obwohl beides angestrebt werden sollte). Zu diesem Zweck kann zu Beginn des Eindickungsverfahrens die Zugabe von Ausflockungs- und /oder oberflächenaktiven Stoffen stehen, gefolgt von Filtrierung und Zentrifugierung. Der Nachbehandlungsprozeß des Filterkuchens dient einer weiteren Herabsetzung des Feuchtigkeitsgehaltes, jedoch sind die vorhandenen Verfahren sehr zahlreich und hängen zudem von der Art des anfänglich ausgewählten Filters ab. Das Endziel einer effektiven Entwässerung ist die Einsparung einer anschließenden thermischen Trocknung des Kohleproduktes und die Herstellung eines transportfähigen Abfalls.

Ausflockungsstoffe können eingesetzt werden, um die Setz- und Filtriereigenschaften der Trübe zu verbessern, oberflächenaktive Stoffe dienen der Herabsetzung des Rest-Wassergehaltes. Derartige Reagenzien können aber in Relation zum Endprodukt teuer sein. Die Filtration/Entwässerung mittels Dampf bietet eine technische Alternative an und kann nützlich sein, wenn Dampf auf der Anlage bereits anfällt. Andere mehr esoterische Verfahren, wie z.B. die elektrokinetische Entwässerung, werden untersucht und könnten weitere Alternativen in der Zukunft darstellen.

Dieser Beitrag stellt die Literatur auf dem Gebiet der mechanischen Entwässerung von Feinkohle und Abfallschlämmen zusammen. Die möglichen alternativen Entwässerungsverfahren werden aufgezeigt und diskutiert und eine Wertung der relativen Vorzüge der einzelnen Verfahren wird vorgenommen.

L'assèchement mécanique de fines et de boues résiduelles

Des procédés alternatifs de séparation solide-liquide offrent une large palette d'installations pour assècher des boues de fines. La signification du choix de la combinaison la plus éfficace de méthodes d'assèchement est mise en valeur par les frais d'énergie qui augmentent et qui sont nécessaires pour des installations de sèchage conventionnelles. Le but, lors du choix d'un schéma fonctionnel précis, devrait être une réduction maximale de l'humidité et non une clarification maximale des eaux résiduelles (bien que toutes deux devraient être recherchées). Afin d'atteindre cet objectif, on peut ajouter, au début de la phase d'épaississement, des substances de floculation et/ou des matières tensio-actives, suivi d'un filtrage et d'une centrifugation. Le traitement ultérieur du tourteau sert à une réduction supplémentaire de la quantite d'humidité. Toutefois, les procédés existants sont très nombreux et dépendent, en plus, du genre de filtre choisi au début. Le but final d'un assèchement éfficace est d'économiser un sèchage thermique du produit houiller et de fabriquer un résidu transportable. On peut ajouter des substances de floculation pour améliorer les propriétes de lavage et de filtration de la pulpe, les matières tensio-actives, elles, servent à réduire la teneur en eau restante. Mais de tels réactifs, en relation avec le produit final, peuvent revenir chers. Ainsi la phase de filtration /assèchement au moyen de la vapeur offre une alternative technique et peut être utile quand la vapeur est déjà existante dans l'installation. D'autres procédés plus ésotériques, comme par exemple l'assèchement électrocinétique, sont examinés et pourraient représenter d'autres alternatives dans l'avenir. Cet exposé rassemble la litterature existante sur l'assèchement mécanique de fines et de boues résiduelles. Les procédés d'assèchement alternatifs possibles sont présentés, discutés et on fait une évaluation des avantages relatifs de ces différents procédés.

El desagüe mecánico de carbón fino y de lodos de desecho

Métodos de separación alternativos solido/líquidos ofrecen una extensa paleta de plantas para el desagüe de lodos de carbón fino. La importancia de la elección de la combinación más efectiva de métodos de desagüe es acentuada por los crecientes costos de energía que tienen las plantas de secado convencionales. El propósito de la elección de un schema de flujo debería ser una disminución de la humedad y nó una clarificación máxima del agua de desecho (apesar que ambas deberian ser logradas). Para lograr esta meta puede estar el aditamiento de medios floculantes y activadores de la superficie al comienzo del proceso para espesar el material. Luego sigue la filtración y la centrifugación. El tratamiento ulterior del residuo de la filtración sirve para una reducción de la humedad, pero existen una gran cantidad de métodos que además dependen del tipo de filtro escogido a un comienzo. La meta de un desagüe efectivo es el ahorro de un contiguo secado térmico del carbón producto y la producción de un residuo transportable.

Medios floculantes pueden ser aplicados para mejorar las propiedades de la pulpa para la deposición y la filtración; medios activantes de la superficie sirven para reducir el contenido restante de agua. Tales reactivos pueden ser caros en relación al producto final. La filtración/desagüe por medio de vapor ofrece

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una alternativa técnica y puede ser útil, cuando el vapor es ganado ya en la planta. Otros procesos más esotéricos, como por ejemplo el desagüe electrocinético son investigados y pueden ser alternativas para un futuro.

Esta contribución presenta la literatura del campo del desagüe mecánico de carbón fino y de lodos de residuo. Las alternativas posibles para el desagüe son mostradas y discutidas, y se dá una evaluación de las ventajas relativas de los diferentes procesos.

Summary

Alternative solid/liquid separation techniques offer a wide range of equipment for the dewatering of fine coal slurries. The importance of selecting the most effective combination of dewatering methods is underlined by the increasing costs of thermal energy required by conventional drying operations. The objective behind choosing a particular flowsheet is to obtain maximum moisture reduction rather than maximum effluent clarity (although both should be attainable). To this end any slurry thickening technique may be preceded by flocculant and/or surfactant addition, and followed by filtration or centrifugation. The cake post-treatment process of dewatering is to minimise final cake moisture contents, but the available methods are wide and dependent on the type of filter initially selected for the duty. The ultimate aim of effective dewatering is to eliminate any subsequent thermal drying of the coal product and to render the refuse in a suitable form for disposal. Flocculating agents may be used to improve the settling/filtration characteristics of the slurry, and surfactants to reduce the residual moisture, but such additives can also be expensive relative to the value of the final product. Steam filtration/dewatering offers a technical alternative and can be useful when a steam supply already exists on plant. Other more esoteric techniques such as electrokinetic dewatering are being investigated and may offer yet further alternatives in the future. This paper will collate the literature pertinent to the mechanical dewatering of fine coal and refuse. The possible alternatives available for coal slurry dewatering will be outlined and put into perspective, and a critique of the relative merits of the procedures involved will be presented.

1. Introduction

Forecasts of energy consumption indicate that coal will constitute a principal source of energy during the next twenty years [1,2], and its role as a feedstock for chemicals production will become more important. This will necessitate increased production and the exploitation of lower quality coal deposits. The production of fine coal and refuse is further increased by the need to reduce sulphur and ash in clean coal products. Although fines have traditionally been discarded, these should be dewatered and utilised for reasons of economics, conservation and calorie recovery; these reasons are listed in Tables 1 and 2.

Current technology offers no dry beneficiation technique which is effective below 48 mesh [3], hence coal preparation plants need to employ a variety of mechanical dewatering processes to effect removal of the substantial moisture picked up by the clean coal and refuse products. In the case of clean coal the amount of dewatering required is related to purchase specifications and the economic and practical constraints imposed by the handling and transportation of a high moisture content commodity. Dewatering requirements for refuse are less well defined, but the plant must reduce the moisture content to a level such that the material can be properly disposed of after suitable treatments. Depending on the amount of finer coal and refuse generated by the particular plant, the dewatering function can constitute a significant proportion of the capital and operating costs.

Table 1: Economic Reasons for Dewatering

1. Wet coal incurs higher transportation and handling charges.
2. Wet coal may freeze and cause difficulty in handling and utilisation during cold weather.
3. Moisture reduces the calorific value of the fuel in combustion processes.
4. Excessive moisture in coke plant charges
   a) increases coking time,
   b) makes oven temperature regulation more difficult,
   c) contributes to damage of coke oven refractories,
   d) increases loads on tar and chemical recovery systems.
5. Wet refuse requires additional energy for handling.
6. Refuse ponds occupy land which may be more profitably used.

Table 2: Environmental Reasons for Dewatering

1. Refuse decantation ponds are unsightly.
2. Pond impoundments can be unstable and constitute a safety hazard.
3. Refuse pond overflows may not be of suitable clarity for recycling or discharging into streams.
4. Refuse pond sediments may not consolidate enough to make the land usable at a later date.

Water not only forms a structural part of coal, but is also naturally present as free water in most coal mines; furthermore, it is the carrier fluid for coal through the beneficiation stages of the preparation plant, and stockpiles and open transportation facilities are subject to the varying climatic conditions. Water, therefore, exists with coal in three forms [4]:

1. Surface water which lies on the surface of the coal particles; this includes moisture held between particles in a coal mass or heap.
2. Capillary, inherent, or structural water which is absorbed into the capillary structure of individual coal particles (to avoid confusion of terminology the latter name will be used here, since much of the so-called surface water must be regarded as capillary moisture when it exists in the interparticle pores).
3. Chemical water which is held in chemical combination, usually associated with certain minerals in coal.

Mechanical dewatering is only concerned with the former class of moisture above, surface water, which is relatively free to move under imposed pressure gradients. The surface moisture content of coal can vary from very small amounts to something greater than 30 %, and is dependent on such factors as the rank of the coal, ambient relative humidity, the composition and mineral concentration in the coal, the particle size distribution, temperature, the mechanical treatments applied to the coal, and the surface and interfacial characteristics of the particles and the water.

Until recent years the disposal of fine refuse (28 mesh x 0) has been by one of several methods: the pumping of fluid refuse behind a permanent impoundment, or the dumping of the material into temporary ponds where the solids are allowed to settle before being excavated and buried into the coarse refuse landfill, or the slurry is dewatered mechanically and the refuse cake is disposed of into the coarse refuse landfill. Mechanical dewatering has probably been practised since the early 1950s, but technical problems caused many plants to abandon refuse slurry dewatering in favour of ponds. It is, however, an intention of many governmental bodies to eliminate slurry ponds by imposing controls and regulations on refuse disposal. Hence, technical attention has been redirected back to mechanical dewatering, and in particular improved designs and techniques in filter installations.

It is the purpose of this paper to present a critique of current practices and recent advances associated with the mechanical dewatering of fine clean coal and refuse. A number of problems which are largely attributable to modern mining methods have arisen in the dewatering and treatment of the fine particles; these problems and their current solutions will be considered.

2. Current Practices in Mechanical Dewatering

Coal preparation plants generate a mass of particulate material which is classified according to size, and separated into coal and refuse (neglecting any other by-products). Centrifugal dewatering is used for coal coarser than 28 mesh and up to about 2.5 cm top size, whilst screens often satisfy dewatering requirements of coarser coal and for refuse coarser than 28 mesh.

A typical layout of a fines treatment plant is shown in Fig. 1, where the flow rates may be representative when the process coal contains a large percentage (40—50 %) of finer

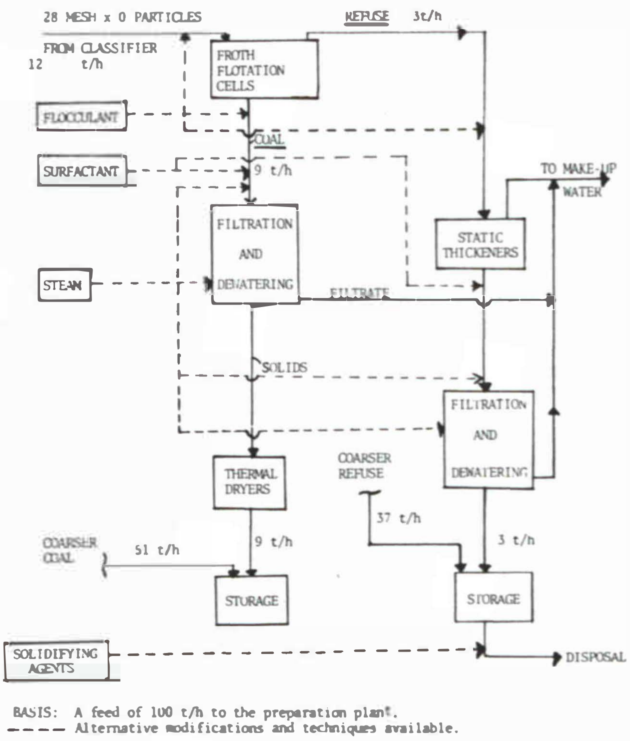


Fig. 1: Fine coal and refuse treatment plant (the flow rates are not typical but indicate the amounts of finer material which may have to be handled)

material in the range of 6 mm x 0.5. From desliming screens the 28 mesh x 0 material is fed to the fine coal and refuse treatment plant, where it may first be treated in banks of froth flotation cells to recover from about 7 % of the feed as clean coal. The clean coal product from the froth cell is then passed to the filter installation for dewatering before being further dried by an indirect type thermal dryer. The refuse from the froth cells goes to a thickener, from which the settled sludge is pumped to a filter where it is filtered sufficiently to permit disposal. The thickening and filtration can be aided by a variety of additives which are aimed at increasing solids throughput rates and lowering their moisture content after mechanical dewatering.

2.1 Slurry Pretreatment

The slurry can be pretreated by the admixture of polymeric or ionic reagents prior to flotation, thickening or filtering. These additives are relatively expensive and careful consideration must therefore be given to their selection and application to coal slurries. The reagents have the primary effect of either flocculating the suspensions, or altering the hydrophobicity of coal to make it more amenable to coagulation or flocculation, or of substantially decreasing the liquid-air interfacial tension to reduce the amount of moisture held by the coal surface.

1. Flocculant behaviour with coal slurries

Polymer flocculants have proven ability as settling and filtration aids. Raw coal slurries may be obtained when froth flotation is considered to be uneconomical; these frequently have an ash content of between 10 and 35 % and flocculants may be used to improve dewatering of such slurries on vacuum filters. When froth flotation is used to yield coal concentrates and shale tailings from raw coal slurries, the ash content is frequently between 3—9 % and 60—75 % for the respective products. Flocculants can provide significant improvements in the filtration characteristics of both these flotation products. However, the coal concentrate can be vacuum filtered without the application of flocculation reagents. On the other hand the tailings product is difficult to filter by vacuum techniques. In Great Britain and Europe pressure filters are considered to be more effective for handling flocculated slurries. Flocculation reagents are useful when ash contents are in the range of 3—75 %, and thus to slurries consisting of almost total coal to almost total shale.

The nature of the solids to be flocculated affects the choice of flocculant. Complex silicate and aluminium minerals dominate in shale; in crushed clay the bonds between oxygen and silicon in Si—O—Si and aluminium and hydroxyl ion in Al—OH are broken to create polar surfaces. In aqueous media H^+ ions react with oxygen sites and OH^- ions with the positive Si and Al sites. Coagulation can be induced by adsorption of negatively charged shale particles to cations formed by the dissociation of added electrolytes such as sulphuric acid, ferric chloride and aluminium sulphate (the trivalent cations tend to give much improved adsorption). On the other hand, the chemical properties of coal depend upon the proportions of the different constituents which were present in the original parent vegetable mass, the extent of the changes which these consituents have experienced, and the inorganic matter present. The zeta potential of coal particles is generally found to be negative but the point of zero charge is dependent upon the particular coal. However, electrolytes appear to be unable to cause coagulation between coal particles much larger than 75 μm. Polymer flocculants seem to offer a better alternative when there is a proportion of coarser particles present. The flocculation achieved by synthetic polymeric flocculants is good when the reagent addition rate and method are carefully controlled. When costs prohibit the use of these polymers either starch based flocculants or simple electrolyte coagulants can offer an alternative. A list of some flocculants useful in coal plants is given in Table 3.

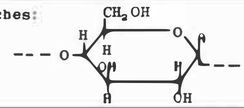
TYPES AND EXAMPLES	REMARKS
Electrolytes: lime, $CaCl_2$, amine derivatives of fatty acids, $FeCl_3$, $Al_2(SO_4)_3$	Higher valency cations (e.g. Fe^{3+}) give better results.
Neutral polymers and polyelectrolytes	Many appear under the trade names of Separan and Superfloc.
Starches: 	Naturally occuring high polymeric carbohydrate, $(C_6H_{10}O_5)_n$, where n > 1000. Both linear and branch polymers exist.
Glues	Groups of polypeptide units
Neutral Polymers: $[-CH_2-CH(C{=}O)(NH_2)-]_n$	Nonionic polymeric compounds of average molecular weight 10^4 - 10^6.
Anionic Polymers: $[-(CH_2-CH(C{=}O)(NH_2))-CH_2-CH(C{=}O)(O^-Na^+)-]_n$	Alkali hydrolysis products of neutral polymers.

Table 3: Useful Flocculant Reagents

2. The use of surfactants with coal slurries

Wetting agents can be used in small amounts to reduce the hydrophobicity of bright coals and hence make them more amenable to coagulation and flocculation. However, the excessive use of such agents is likely to affect adversely adsorption of flocculant by creating an overconcentration of the counter ion in the double layer.

The primary reason for using surfactants is that at very small concentrations in aqueous solutions they decrease substantially the liquid-air interfacial tension of the solution. Surfactants are ionic or polar derivatives of high molecular weight hydrocarbons and are amphiphilic, that is, one part of the molecule has an affinity for water (hydrophilic) and another has an oil affinity (hydrophobic). Both ionic (anionic and cationic) and non-ionic surfactants exist. The reduction obtained in interfacial tension produces a lower residual moisture content in dewatered filter cakes, and a side effect of this is that more air is drawn through the cake due to the more rapid reduction of moisture content. The selection of a suitable surfactant to dewater a particular coal is difficult and must rely on small scale dewatering experiments; it has been found that, in general, any surfactant will provide a lowering of residual moisture but with some the lowering is rather more substantial. A list of useful surfactants is given in Table 4; these have given improved moisture content reductions during vacuum dewatering of 26—47 % over that obtained when draining water alone [22].

2.2 Choice of Dewatering Equipment

From the point of view of the considerations pertinent to this report the choice of dewatering equipment is tantamount to the selection of filters to fulfil the filtration and dewatering functions in Fig. 1.

Trade Name	Chemical Name	Molecular Weight a.m.u.
Aerosol A-196 (anionic)	Sodium dicyclohexyl sulfosuccinate	384
Aerosol OT (anionic)	Sodium di(2-ethylhexyl) sulfosuccinate	444
Triton X-114 (non-ionic)	Octylphenoxypolyethoxy ethanol	536
- (cationic)	Dodecyl pyridinium chloride	284
- (anionic)	Sodium dodecyl sulphate, also known as sodium lauryl sulphate	288
- (non-ionic)	Polyoxyethylene	-

Table 4: Some Useful Surfactants for Coal Slurry Dewatering

1. Vacuum filtration

In the USA the disc type vacuum filter is the principal piece of dewatering equipment used in the coal preparation industry for handling clean coal and refuse with large amounts of material smaller than 28 mesh. Such units are used to reduce moisture contents of froth concentrates from flotation prior to thermal drying, as well as to handle static thickener underflows.

A vacuum disc filter consists of a series of disc shaped leaves mounted vertically. A vacuum is pulled within the leaves, of which almost the lower half dips into the slurry trough. The discs are covered on both sides with a fine mesh filter cloth or other suitable filter medium which will not be binded or clogged by the particles being separated from the slurry. The discs are mounted on a hollow shaft, with pipework allowing a suction pressure to be applied to the surfaces of each disc, as well as facilitating withdrawal of the filtrate collected. The slurry to be dewatered is fed into a trough, and cake formation takes place on the submerged portions of each disc. The discs rotate so that the cake is carried out of the slurry whilst vacuum is continuously removing water from the cake voids. Air flow rates averaged over the total cycle are typically 5 $ft^3/min/ft^2$ for froth concentrates and 3 $ft^3/min/ft^2$ for thickener underflows; solid throughput rates are in the region of 40—60 $lbs/h.ft^2$ when dewatering clean coal and about 20 $lbs/h.ft^2$ for refuse.

2. Centrifugal dewatering equipment

Centrifugation is useful for the dewatering of fine coal and refuse slurries with particles in the 28 meshx0 range, the most suitable types of centrifuge being the screen bowl and the solid bowl with scroll conveyor discharge of the solids.

Whereas the moisture content of coal cakes on a disc unit is normally around 20 %, moisture contents of about 14 % can be expected from a centrifuge whilst 96—98 % solids recovery is achieved. These machines have a horizontal configuration and the separation takes place in two stages: in the solid section of the bowl centrifugal force removes most of the liquid and produces a particulate bed around the bowl walls, these solids are moved by a scroll conveyor along the centrifuge and through a perforated section of the bowl where further dewatering is effected. The solids are ultimately scrolled out of the machine, and discharge of both solids and centrate streams is continuous. Typical throughput rates for these machines are in the range of 5—75 t/h.

Also useful for finer separations are the horizontal solid bowl scroll discharge centrifuges. These machines are horizontal and have two principal elements; one is the rotating bowl which is the settling vessel and the other is a scroll conveyor which advances the settled solids to the discharge ports. The clarified liquid and the solids are discharged continuously at opposite ends of the machine. Typical capacities of these units are in the range of 2—30 t/h.

Although centrifugal equipment requires substantial power to accelerate the feed slurry, the power requirements are often approximately 50 % less than comparable capacity vacuum disc filter installations. Capital costs of centrifuges are significantly higher than they are for the disc filter counterparts, but this must be evaluated in terms of the unit's performance and the potential for lower operating and maintenance costs (and the possible impact on reducing thermal dryer capacities). Solid bowl centrifuges may often require a secondary thickener on the centrate stream to produce an underflow with 25 % solids which can be filtered on a rotary vacuum drum filter — the centrate cannot always be returned to the primary thickener as fines may tend to build up in the system and eventually cause shutdown of the water circuit.

3. Plate and frame filters

In Great Britain and Europe the automated plate and frame filter has gained wider acceptance as the preferred type of filter for the dewatering of refuse slurries. More serious consideration may need to be given to this machine by the U.S. coal industries since the operation of the disc filter and the solid bowl centrifuge is marginal when handling 75—85 % ash refuse with 70 % —200 mesh. To give an example of the ash refuse handling capacity of filter presses, two 100 frame 1.32 m square filters would offer a filter area of 288 m² and a cake capacity of 16.6 m³. Such presses would typically operate on a 2 hour cycle and would handle 12.5 t/h of high ash refuse; the cake discharged would be 5—10% lower in moisture than can be achieved with the disc filter and the solids removal would be 100 %.

Although there is a general divergence of practices between different countries when dealing with ash refuse, it would appear, however, that vacuum filtration is the preferred technique for fine coal dewatering.

3. Existing Problems

Problems with media binding, low filtration rates, high cake moisture contents and high maintenance costs caused many plants to abandon refuse slurry filtration in favour of ponding. In recent years a number of governments have caused filtering techniques to be reappraised by the imposition of regulations, guidelines and standards relating to the construction, use and ultimate abandonment of refuse slurry or tailings impoundment dams. Continuous mining methods and the need to release pyritic sulphur have increased the quantity of —28 mesh fines in coal, and in order to offset the high moisture contents normally associated with finer size fractions the industry has found it necessary to increase both capital and operating costs for various types of thermal drying units. Whilst the industry has been able to achieve the required overall final product moisture content, operating hazards such as dust explosions and air pollution are problems. Furthermore, energy costs are making thermal dryers increasingly more expensive units to operate, and it must be an ultimate desire within the coal industry to eliminate thermal dryers from flow sheets whenever possible.

The production of larger quantities of fine material can be traced as the cause of a number of existing problems associated with the mechanial dewatering of coal. The more major problems can be listed as follows:

1. binding of filter media,
2. less than 100 % solids removal causes fines in filtrates and possible fines build-up in recirculating water systems,
3. high moisture contents of solids discharged from filters,
4. disposal of refuse and the stability of disposal sites,
5. explosion hazards in thermal dryers, and air pollution generation.

Items (3), (4) and (5) above may well be improved when better dewatering is obtained and improved techniques are used. They are not in themselves mechanical dewatering problems but are directly affected by earlier dewatering of the solids. Although these factors must be mentioned here, the primary task is to reduce the influence and hence impact of problems (1), (2) and (3).

4. Existing Solutions to Current Problems

The first step in reducing cake moisture contents, whilst at the same time maintaining a high filtration rate and good filtrate clarity, is appropriate choice of equipment for the specific duty. Drum and disc filters, centrifuges and plate and frame filters have all been used with some degree of success. New developments in filter equipment offer an expanding choice to the design engineer. Horizontal belt filters and automatic variable chamber diaphragm presses would appear to be two types of the newer breed of filters worthy of very serious consideration for fine coal and refuse dewatering [12, 37, 57]. General approaches to the selection of solid/ liquid separation equipment appear in several texts [38—41] and it is worth consulting these when faced with a fresh problem or proposals for a potential installation.

Having selected a filter, the variations to existing practices must then be investigated to determine which offer the best advantages in terms of minimising the cake residual moisture content for each particular application. These fall into the general categories of:

- slurry pretreatment (e.g. surfactant or flocculant addition, slurry preheating)
- cake post-treatment (e.g. steam dewatering, use of infrared radiation or mechanical aids).

4.1 The Use of Surfactants and Flocculants

It is important to distinguish between the different mechanisms involved and the likely effects of using surfactants and flocculants. Surfactants will either produce a reduction in the surface tension of the water or will adsorb onto the solid surface to make the particles more hydrophobic, and should result in a cake having a lower moisture content. Flocculants, however, work by changing the apparent particle size and therefore will alter the pore size distribution in the cake, its compressibility and its drainage characteristics. Sometimes the filtration rate is increased due to the increase in apparent particle size but, due to the different pore structure, higher final moisture contents can result.

Initial testing of a flocculant is suitably carried out in a series of jar sedimentation experiments to determine the optimum dosage — that is, the dose which gives either the maximum settling rate or the most rapid build-up of the sludge layer. This optimum dosage must then be tested in a filtration experiment to ensure that cake moisture contents are not adversely affected — some typical results are given in Fig. 2

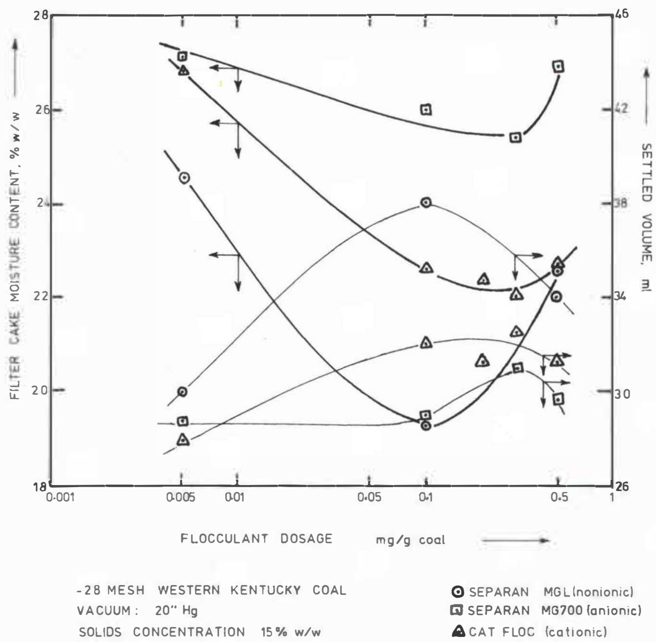


Fig. 2: Effect of flocculant dosage on filter cake moisture

which also indicates the effect of an overdose causing a substantial rise in cake moisture. Careful evaluation of the dosage around the determined optimum is necessary to obtain the best dosage to yield the minimum moisture content. Research into the use of polymeric flocculants with fine coals indicates that:

1. the reagent dosage generally decreases with increasing molecular weight for a specified polymer type,
2. the effect of slurry concentration in optimum dosage is complex. For some flocculants the optimum dosage varies inversely with slurry concentration, attributable to improved bridging mechanisms and enhanced adsorption at higher concentrations. For others the optimum dosage is independent of slurry concentration — this result also appears to be generally true when the solids concentration (expressed as [mass solids/mass liquids] x 100) is greater than 30 %.

Further claims can be the reduction of coal losses, increases in the capacity of filters (in particular vacuum filters), a reduced tendency for media to bind, as well as decreased moisture contents of fine coal cakes.

When a higher cake moisture content is experienced with a flocculant, whilst all other factors appear more favourable, this may be attributable to the bimodal porosity distribution typical of flocculated filter cakes. Mechanical pressure can be used to reduce the overall cake porosity, and hence the use of variable chamber diaphragm presses may offer a technical alternative for lowering the moisture content. As the costs of thermal drying increase, variable volume filters become more competitive with other alternatives on economic grounds for the dewatering of less compressible media [65].

The testing of surfactant suitability is necessarily by means of filtration and cake dewatering experiments to ensure that lower moisture contents are obtained. A plot of the solution surface tension versus dosage readily determines the amount of surfactant needed to reduce significantly the surface tension, and by how much the tension is lowered. However, such experiments must be carried out with a weighed amount of the solids added to the solution to determine the extent of surfactant adsorption onto the coal or refuse surfaces, and hence the "true" surface tension reduction. This is indicated in Fig. 3, where it is seen that the presence of the solids may cause the surface tension reduction to be mini-

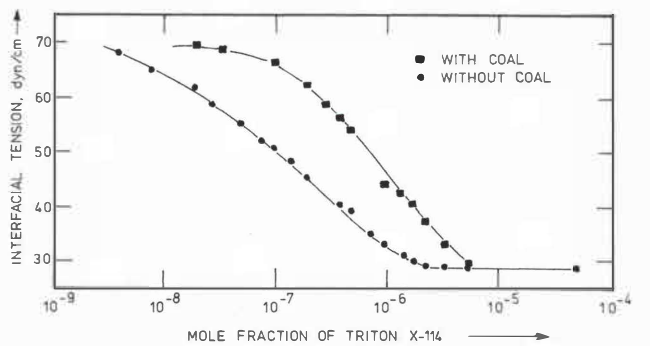


Fig. 3: Liquid-air interfacial tension of aqueous solutions of Triton X-114 in contact with an adsorbent coal sample

mal, but the particle hydrophobicity is affected. In such cases it is possible to select judiciously a mixture of two different surfactants, so that any advantages of both lowering the surface tension and increasing the particle hydrophobicity can be assessed.

It would seem that variable results have been obtained by the use of polyelectrolytes and surfactants. This may be a reflection of the adsorption characteristics of the materials tested and a lack of understanding of the operating mechanisms of different surfactants in dewatering processes; further work is necessary to systematise experimental techniques and provide a better fundamental basis for such studies. The long term effects of these reagents in closed water circuits require careful attention.

4.2 The Use of Warm Feed Slurry

In small scale tests preheating the slurry prior to filtering has indicated that cake moisture contents would be reduced by $1\,^1/_2$—2 % [66]. In large scale tests these improvements were not always realised. Quite large amounts of heat were required to warm the entire feed, and higher slurry temperatures result in the deposition of thicker cakes in similar form times. Also, the filtrate has a greater tendency to flash. The thicker cake in fact leads to an increase in moisture content, counteracting the benefits which might have been expected to result from the lower filtrate viscosity. If the slurry has a relatively high solids content preheating by steam may be feasible, and potentially offer an effective treatment process to aid the production of lower moisture content cakes.

4.3 Air Sucking or Blowing

This is the standard technique of dewatering the cake on rotary vacuum filters. It immediately follows the cake formation stage, when air is sucked through the cake as the latter emerges from the slurry. Moisture is consequently displaced.

After a certain time the rate of moisture removal is reduced and very little advantage is to be gained by extending the dewatering time beyond this point. Formulae exist which enable compensating changes to be calculated for certain of the variables if one or two of the other variables have, for some process reason, to be changed whilst at the same time cake moisture must be maintained.

Before any saturation reduction can be achieved a minimum force must be exceeded in order that air may enter the filter cake. This so-called threshold pressure is correlated as:

$$p_b = \frac{4.6\,(1-\epsilon)\,\gamma}{\epsilon d} \qquad (1)$$

where

p_b = threshold pressure (N/m²)
ϵ = cake porosity
γ = surface tension (N/m)
d = mean particle size (m)

The kinetics of cake dewatering are difficult to calculate, although some approximate methods are available [71, 74]. When removing filtrate by air flow the quantity of air flowing through the cake is important, as this controls the necessary installed vacuum pumping capacity. During the cake drying cycle the air flow increases from almost zero to a maximum when the cake is almost dry. The cake moisture content approaches an irreducible level asymptotically. For hydrophilic particles the corresponding saturation level can be estimated from:

$$S_\infty = 0.155 \left\{1 + 0.031 \left(\frac{\epsilon^3 d^2 (\varrho g L + \Delta p)}{(1-\epsilon)^2 L \gamma}\right)^{-0.49}\right\} \qquad (2)$$

where

S_∞ = the irreducible saturation level
ϱ = filtrate density (kg/m³)
g = acceleration due to gravity (m/s²)
L = cake depth (m)
Δp = pressure drop across the cake (N/m²)

Hence, for any improvement in final moisture contents the porosity of the cake, the size of the particles forming the cake, the pressure drop or the surface tension of the fluid must be altered. In general, if the particles are more hydrophobic the irreducible level can be expected to be lower.

Since air sucking is the standard technique employed on vacuum filters the primary concern in this paper is to improve this process by suitably adjusting conditions or modifying the operating procedures.

4.4 The Use of Infra-Red Radiation

The problems associated with this technique are similar to those experienced with hot gases, viz. low cake permeabilities and low heat capacities of the heating medium lead to long times required for drying. Due to the opacity of most substances to infra-red radiation, heating is mainly confined to the layers of cake lying near the surface which become raised in temperature with possible consequent degradation of the coal product, while the lower layers remain undried. If applicable at all it would only be applicable to vacuum drum or belt filters — but a radiation panel maintained at 850 °C at 70 mm from a coal cake surface causes ignition of the solids in less than one minute [75]. It is unlikely that infra-red radiation will be useful technique in fine coal and refuse dewatering.

4.5 The Use of Steam to Improve Cake Dewatering

The most successful heating medium appears to be superheated steam which is applied to the surface of the cake. Penetration of the steam and subsequent condensation in the pores of the cake lead to the formation of a "condensation front" (Fig. 4). Ahead of the front is a mixture of condensate and residual filtrate which effectively prevents steam

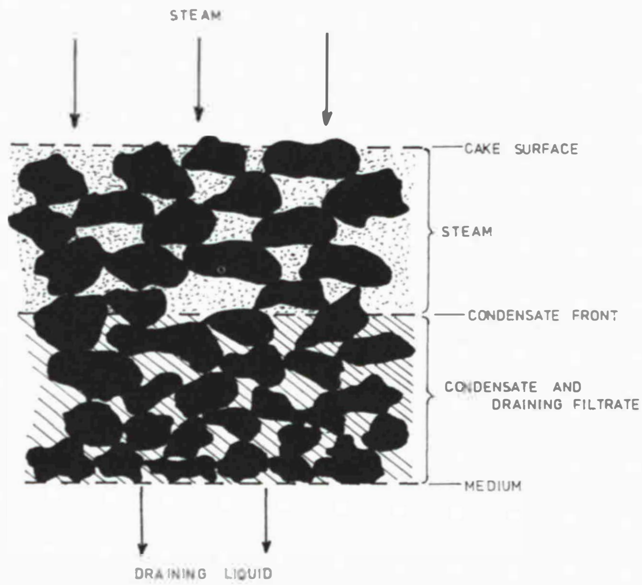


Fig. 4: Mechanism of steam dewatering

penetration into the filter medium (and hence into the filter drainage passages), whilst behind the front the cake voids are largely filled by steam. Using steam carrying about 25 °F superheat the heat transfer is sufficiently rapid to warm the cake in the limited time available — too little superheat would warm the cake inadequately and the net result can be cake with a higher moisture content when the steam condensation has not yielded enough heat to lower the filtrate viscosity and surface tension. On the other hand, too much superheat or too great a supply of steam will cause product degradation. There is, of course, a temperature gradient within the cake across the condensation front. Behind the front the maximum possible temperature at any point is the boiling point of water at the absolute pressure which exists at that point. At the end of steaming the temperature gradient varies from the atmospheric boiling point of water on the outside to the vacuum equivalent boiling point at the filter medium.

From the practical point of view steam dewatering necessitates the use of a steam hood capable of:

— maintaining dry steam above the cake surface,
— preventing steam escapes, and
— preventing air leakages into the steam.

As the condensation front forms a barrier to gas flow through the cake, any infiltrated air cannot escape until after the front has penetrated the medium. Since air and steam form a homogeneous mixture some of the steam heat will go to warm the air and lower the efficiency of steam usage (but the passage of small quantities of air may well go unnoticed).

Steamed filter cakes contain considerable sensible heat which should be used to evaporate some of the residual moisture content. This cooling of the cake can be carried out by a conventional air sucking dewatering operation when the cake is sufficiently porous. Steam flow into the hood is controlled by the use of a temperature or pressure sensor in the hood which regulates the steam control valve. Excessive pull-through of raw steam is prevented by sensing the temperature beneath the cake at the end of the steaming zone (or in the steam zone vacuum receiver) and using this to regulate the steam zone vacuum level.

The quantity of steam required can be reliably estimated from heat balance calculations, and using a multiplying factor of 1.4 to account for excess steaming time and system inefficiencies. The data in Fig. 5 may be helpful for such calculations.

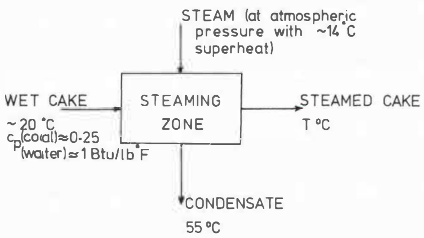


Fig. 5: Some heat balance data for steam dewatering calculations

There is some advantage to be gained in allowing steam to follow the slurry liquor immediately through the cake without an intermediate air dewatering; but some type of top-loading filter is required to apply this technique, such as a horizontal belt filter. Operating in this way precludes the possibility of some of the finer pores in the cake becoming air locked, whence the cake heating is incomplete.

During air dewatering following steaming (sometimes referred to as the evaporative cooling period) the cake moisture content decreases rapidly because of the lower residual filtrate viscosity and the residual moisture content is lower because of the decreased surface tension and more rapid moisture withdrawal. Concomitantly the air rate rises sharply leading to relatively high instantaneous rates. In general, the total installed costs of a steam filter unit and a standard ambient filter plus a thermal dryer are comparable; and the higher power costs for steam filtration are more than offset by the much lower fuel and maintenance costs. Effective steam dewatering schemes are summarised in outline in Fig. 6.

4.6 The Use of Mechanical Aids

These devices are used to attempt to bring the particles forming the cake closer together, reducing capillary sizes and so forcing any excess water to be released and removed. They also represent an attempt to close up cracks in the cake which lead to a serious loss of filtration driving force. The methods used are either:

1. rolls held on the filter cake by weights or hydraulic pressure to exert a squeezing action, or
2. soft rubber flappers mounted on a rotating shaft which are allowed to slap the cake and induce particle rearrangements and hopefully liquid expulsion.

These are most useful with rotary drum filters and may not prove a useful alternative in coal filtration.

4.7 Alterations to the Vacuum System

The vacuum applied in a filtration operation may, for the purposes being discussed here, be divided into two: 1) the form or pick-up vacuum, and 2) the dry cycle vacuum. Equipping a disc filter with two vacuum systems and two filtrate pumps enabled the operation to be carried out in three ways:

1. With a single vacuum system drawing 4—5 $ft^3/min/ft^2$.
2. With separate pick-up and dry vacua.
3. With increased total vacuum capacity.

Full scale testing gave the following results:

— a 33 % increase of filter capacity and a decrease of moisture content from 20 % to 19 % by increasing the filter vacuum from 15 in Hg at 5 $ft^3/min/ft^2$ to 20 in Hg at 7 $ft^3/min/ft^2$, and

— the use of dual vacuum system and a slow disc speed (4 min/rev) reduced the moisture to 17.5 %, but filter capacity dropped by 20 % compared with normal operation at 5 $ft^3/min/ft^2$.

Although some improvement may be interpreted from these results it is most likely that the filter cake structure and the physical properties of the solid and fluid would prevent any significant moisture content reduction provided the filter is properly designed in the first place and good housekeeping is observed.

4.8 Solidification of Fine Refuse

After mechanical dewatering the fine refuse can be treated with an additive such as Calcilox to produce a solidified mass with dependable engineering properties. The treated refuse develops substantial shear strengths and low permeability and behaves as a consolidated solid so that construction properties of the stabilised material can be predicted reliably. This is an important aspect contributing to the elimination of disposal ponds; the general problems and future needs for long term lagoons have recently been reviewed [89], and it was concluded that tailings lagoons are likely to remain a widespread method for the disposal of slurry wastes (although this may not be quite so true in the case of fine coal tailings).

5. Experimental Testing Techniques

No *standard procedure* for test or scale-up procedures exists when mechanical dewatering is being considered. There appears to be wide differences between the techniques and procedures used by different suppliers of very similar types of equipment, but the general principles applicable to obtaining information should be adhered to when carrying out field and laboratory leaf tests for cake formation and dewatering data. These can be summarised as:

— Obtain and use in the test a representative sample of the process slurry

— Measure the particle size distribution, the true density of the solids, fluid viscosity and density, solids concentrations, and temperature to establish test result bases for comparative purposes.
— Use a suitable filter cloth giving maximum filtrate rate and clarity.
— Laboratory tests must be performed at the pressure or vacuum level expected on the actual filter.

A leaf filter test rig should be designed so that all pertinent variables are measurable during both cake formation and cake dewatering. For the former these data should include:

1. a recording of the filtrate volume collected as a function of time,
2. the pressure difference applied across the filter medium and cake, and
3. the depth of the deposited cake and the mass of solids contained therein.

The additional necessary measurements for the analysis of cake dewatering experiments are:

1. recordings of both the air flow rate and the filtrate volume collected as a function of the dewatering time,
2. the surface tension of the filtrate,
3. the pressure difference applied to effect cake dewatering.

If tests are being run on materials which form a relatively porous cake, care must be taken during experimentation that it is the cake and not the pipework on the test facility which is limiting the air flow. With such materials large vacuum pumps or permanent vacuum lines should be used as smaller pumps frequently do not have sufficient capacity to yield the appropriate design criteria. To obtain air rate data it is preferable to use a measuring device giving an electrical signal as output which can be monitored on a chart recorder. Alternatively, a positive displacement meter can be used to determine the total volume of air which passes through the leaf during a test. When a rotameter or some other type of instantaneous reading meter is used, the rate vs time data must be integrated to obtain the appropriate air flow for the design. To avoid confusion air rate values should be reported in full, e.g. m^3/s (m^3 of total filter area) measured at 0.5 m Hg vacuum and 20 °C.

6. Filtration Fundamentals

In the filtration of solid particles from liquids by use of a filter medium a mechanism of surface deposition is invoked in which the filter medium characteristics are unchanged during the process. In these circumstances a relationship may be derived between the filtrate volume, V, collected in process time, t:

$$\Delta p = (K_1 V + K_2)\, dV/dt \quad 3)$$

in which Δp is the available pressure drop, K_1 is related to the filter cake resistance and K_2 to the medium resistance by:

$$K_1 = \bar{\alpha} c \mu / A^2 \quad (4)$$

$$K_2 = \mu R / A \quad (5)$$

where $\bar{\alpha}$ is the average filter cake resistance, c the solids concentration, μ the filtrate viscosity, A the filter area, and R is the medium resistance. To obtain relationships between solids yield W (kg/s m²) or filtrate volume and time, equation (3) must be integrated. The final (V, t) or (W, t) results will depend on the conditions of integration.

It has generally been recognised [92] that the filter cake resistance is pressure dependent. Particle concentrations have been shown [91, 93—95] to have effects on the structure of filter cakes. The surface deposition referred to above is obtained only at higher concentrations, whilst at lower solids concentrations there is a greater tendency for some particles to enter the pores of the filter medium and give rise to higher apparent specific resistance. A principal contribution to the understanding of filtration mechanisms followed the realisation of the influence of particle concentration and movement in the displacement of fluid in filters [92].

Despite the volume of information available concern has been expressed [95] on the lack of application of theory to practical design and in the interpretation of plant outputs. It is generally considered that pilot-scale evaluation is essential in the development of filter design and specification, and that use of published data on the filterability of the slurry of interest (if available) should not be encouraged without practical trials. Given adequate trials, application of the theoretical relations should give reliable estimates of plant capacity or performance.

The fundamentals of cake dewatering are rather more difficult to simplify, and are dependent on the dynamics of simultaneous air and liquid flow through the filter cake. The practical aspects of this problem have been elucidated and are best understood by referring to the original techniques developed for design purposes [41, 70, 74].

7. Modern Filtration Technology

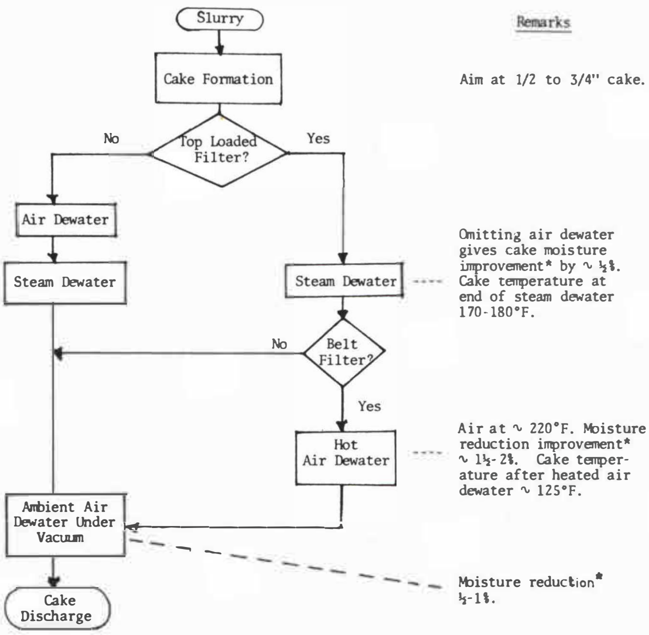
For the mechanical dewatering of fine coal and refuse the coal industry has generally used a relatively limited variety of solid/liquid separation equipment for a number of technical reasons. Equipment development in recent years has led to the exploitation of more techniques to yield lower moisture content cakes; this has led to the introduction of new filter machines which may well find some applications in the coal industry.

In the field of vacuum filtration the emergence of the horizontal belt filter [56, 97, 98] is probably most pertinent to fine coal processing. This filter is basically constructed as an endless belt so it does not have the dead time factors built into it in the same way as vacuum drum and disc filters. Generally, with drum and disc filters the finest particles in the suspension are the first to contact the filter medium (although not so with top feed filters) and hence result in a lower filtrate rate. Belt filters overcome this problem as they are top fed, and they are more versatile than other types of vacuum units. Thick cakes can be used, cake formation and cake dewatering times can be varied to greater extents, as well as the machine operating conditions. Cake dewatering aided by steam or hot air is quite possible and so the advantages set out in Fig. 6 may be attainable.

With the growing interest in energy conservation and for the reasons set out in Tables 1 and 2 filters are required to produce cakes of the greatest possible dryness. Membrane pressure filters have frequently provided a solution in other industries; these are variable volume filters provided with a means of squeezing the cake after deposition. The availability of many types of variable volume filters on the commercial market is comparatively recent. The types can be categorised into:

1. variable chamber filter presses,
2. tube presses, and
3. belt presses.

The first type may find some application to coal and refuse dewatering, particularly if flocculation has tended to render the cake wetter on more conventional filters. However, any lowering of cake moisture contents will be at the expense of additional capital and running costs, and comparative economic analyses of the filter and dryer performances will need to be carried out for each individual application.



* Moisture content improvement over "untreated" cake – these improvements are cumulative in their effect, but each additional step results in a longer cycle time and thus a decrease filtration rate.

Fig. 6: Flowchart for steam treatment of filter cake for effective dewatering

8. Further Possible Improvements in Coal Dewatering

To gain further improvements in moisture contents the fundamental aspects which relate to cake moisture reductions must be considered. The following list may serve to indicate some of the factors which might be adjusted or controlled to effect an improvement.

1. Cake formation — the production of thin cakes facilitates easier dewatering.
2. Delayed cake formation — the filter may be used as a thickening device over part of the cake formation stage to remove larger volumes of water at the filtration [99—101]. It seems unlikely that lower moisture contents will be obtained using this technique.
3. Cake porosity — a stable open pore structure can sometimes be achieved by the use of flocculants, or by grading the solids into narrower size ranges [102]. A flocculant stabilised pore, however, must not collapse when an air/water interface passes through the pore.
4. Cake permeability — high permeability is desirable for fast filtration, and can usually be associated with a high porosity (although it can be solely due to a large particle size). If a flocculant induces a high permeability by the creation of relatively few large active pores, it can have a deleterious effect on the residual moisture levels.
5. Filtrate viscosity — a reduction in viscosity is likely to be beneficial both to filtration rates and to dewatering rates.
6. Surface tension — a reduction in surface tension is beneficial to dewatering and obtaining lower moisture contents.
7. Differential pressure — the benefits of increasing differential pressure are too well known to be further expanded upon in this report. However, there is a "threshold pressure" which must be exceeded before the liquid held in the cake pores can be expelled [68].

Some of the variables mentioned above are largely fixed by the type of filter selected. As discussed in previous sections, there is scope for changing some by the use of chemical additives, and manipulations of most of these variables have been attempted one way or another. However, systematic studies of those listed above are generally lacking, and a study related to a particular solid/liquid system may provide more encouraging results than have been reported in the literature. To the above list could be added three special techniques which might help to reduce moisture contents and which are different from any discussed in the previous sections:

8. Ultrasonic dewatering — ultrasound has been used to aid the filtration and dewatering of closely graded coal, and was found to give lowered residual moisture contents. With a sound pressure level of 160 dB the cake moisture content was reduced from 24.5 % to 21 % for particles in the size range 50—75 μm, and from 21 % to 17 % for the size range 75—100 μm. The pressure drop was 68 kn/m² in each case [103—107].
9. Electroosmotic dewatering — the application of a D.C. potential across a low permeability bed creates electroosmotic flow of the fluid and a substantially increased rate of dewatering, whilst the consumption of electrical power is minimal [108—112]. It is expected, however, that the value of this technique will decrease as the cake permeability increases (that is, when the cake is composed of larger particles or is more porous).
10. Oil assisted dewatering — oil addition to a suspension of hydrophobic coal particles causes agglomeration of the coal, thence improving drainage rates, solids recovery and equilibrium moisture contents [113—125]. The mechanisms of the technique are not new and reductions of coal cake moisture from 27 % to 10 % have been reported by adding 3 % kerosene before filtering [123].

9. Concluding Remarks

1. There is likely to be continued interest in minimising moisture contents of fine coal and refuse filter cakes.
2. Slurry treatment prior to filtration by flocculants and surfactants can yield some benefits, but may not be cost effective. Systematic studies of the usage of these additives in the context of fine coals are needed to improve the understanding of dewatering phenomena.

3. Theoretical models exist which enable preliminary estimates to be made of the final cake moisture content and the length of time and volume of air required to accomplish cake dewatering.
4. Application of filtration theory should give reliable estimates of plant capacity or performance after adequate practical trials have been carried out.
5. The use of steam can be an effective aid to cake dewatering.
6. Horizontal belt vacuum filters and membrane pressure filters should be considered as technical alternatives alongside centrifuges and conventional filters when new plant proposals are being evaluated.
7. Further research is required to assess the potential of electrofiltration and ultrasonic dewatering to the mechanical dewatering of fine coal and refuse slurries.

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