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# DRY CLEANING OF COAL: REVIEW, FUNDAMENTALS AND OPPORTUNITIES

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(8 figures)

**ABSTRACT.** Arguments are given for dry or for wet separation of coarse coal and shale. An overview is given of dry treatment methods for run-of-mine coal used successfully, now and in the past. Examples are given of separators based on gravity force in combination with the material properties density, friction, and resiliency. Specific details are given of fluidised sand separators. Current improvement potential for the dry separation of coal is discussed. Results of experiments with a pilot size dry fluidised sand separator are shown.

**Keywords:** coal, density, separation, dry processing, gravity, table, fluidised bed.

## 1. Background

Most of the coal presently being consumed is by direct combustion of finely pulverised coal in large-scale utility furnaces for the generation of electric power. Currently, the cleaning of the majority of run-of-mine coal is conducted by heavy medium separation, jigs and chemical flotation. These techniques use water as a separation medium. The use of wet separation techniques is accompanied with the generation of large amounts of coal slurry, which is used as a replacement fuel for oil-fired boilers and other furnace systems. By studying the historical development of dry processing during the last century it is explained why wet processing currently dominates coal preparation. Past experience forms an important basis for improving dry separation to be more competitive and benefit from its specific advantages in modern operations. Successive improvements on dry fluidised bed separation were investigated at Delft University of Technology in the light of an ECSC sponsored project on dry separation technology that is carried out in co-operation with Nottingham University (United Kingdom) and RWTH Aachen (Germany).

## 2. Dry or wet coal preparation?

State of the art coal processing today is wet, however, dry gravity processing opens better possibilities for down scaling, being less restrictive for small capacities allowing on-site separation with less transportation cost. Further, mobile operations are easier to operate without a water circuit, also temporary operations and underground operations can be conducted at lower cost.

Arguments for and against dry or wet processing are extensively described in more dated publications from the last century (Arms, 1924; Chapman, 1928; Carris, 1950); and in more recent publications (Lockhart, 1984, Zhenfu, 2002). They illustrate the benefits and drawbacks of dry and wet processing of coal. Decision criteria are explained in the following list and based on moisture content (2.1), availability of separating medium (2.2), dry (2.3) and cold regions (2.4) and properties of coal and accompanied materials (2.5).

1. It is hardly an advantage to reduce the ash content of a coal by cleaning it and simultaneously increasing its moisture content. Sometimes the water content exceeds 10%, slurries may contain 30% water. Whenever fine crushing is needed to liberate product from gangue, the more cost-effective dry fluidisation could be the alternative to the present costly recovery with wet chemical flotation (Tanaka, 1996).
2. The availability of air as the separating medium is abundant and offers no difficulties. Air can be satisfactorily filtered from fine dust. In many collieries the supply of water is not abundant, and the disposal of the spent water is not always easy. Dry processing allows for mobile installations to operate at reduced cost.
3. Dry arid climates in many parts of the world e.g. South Africa and other parts of Africa, Australia, Asia, in particular China (Yongren, 2001, Zhenfu, 2001 and 2002) and certain areas in the USA often leave no other option than dry processing. More generally dry processing must be applied wherever water supplies are limited relative to the demand, or are expensive to obtain, or are of low quality, or some combination of these factors.

4. A considerable advantage is acquired in areas where the temperature is below the freezing point of water for part of the year (Lochmann, 1979). Arctic regions require certain precautions regarding the processing of coal whether wet or dry. In arctic Europe, Russia and certain parts of Northern America, where the winters are cold and the coal must travel some distance by rail or road, coal will tend to change into a frozen mass, giving severe handling problems. Some mines ship their coal during summer only, and others confine their sales during the winter to markets that will take unwashed material. Some mines in the past are believed to have added anti-freeze to their wash water.
5. Wet processing often is not the appropriate method because of inefficiencies due to:
   - Chemical breakdown of contained materials.
   - Physical degradation leading to excessive fines – this is common with very friable materials and when clays are present.
   - Handling problems, environmental hazards, excessive water consumption and losses.
   - Insufficient density difference between components.
   - Difficult floatability of the coal, and excessive energy consumption and/or high costs for chemicals used in flotation.

The given arguments justify the conclusion to weigh up the pros and cons given the circumstances mentioned to process the coal dry or wet. Despite the fact that technology has changed, the arguments discussed and presented in the articles almost a century ago are equally valid today. Actual disadvantages of dry processing are the health risks encountered during separation, another risk is the danger of explosion and fires. Today dust prevention by means of water jets is a necessity, resulting in minimum moisture content of the coarse particles. For moist coarse coal dry separation techniques can only be successful when their performance is insensitive to variations in this residual moisture content.

## 3. Review of some dry separators for coal

Dry and wet separators for coal are derived from just a few principal unit operations, which are already known from the 16th century and earlier (Hoover, 1950). They comprise the principle mechanisms of buoyancy, settling, fluidisation, film flow, rotation and oscillation (Jong, 1999). By combining and further developing them, specifically density separation techniques gradually evolved to the technology as we know it today. These techniques can be employed both dry and wet. The first concise handbook which includes separation technology for solid particles, was published in 1556 by Agricola in his De Re Metallica (Hoover, 1950). More recent textbooks present a comprehensive range of jigging and fluidisation equipment, as well as their applications (Taggart, 1945; Kelly, 1982; Burt, 1984; Weiss, 1985; Schubert, 1996). More specific for coal separation techniques the following references are given: Schennen, 1913; Chapman, 1928; Blumel, 1930; Mitchell, 1942; McCulloch, 1968 and Frankland, 1995. Fig. 1 gives an overview of the development of principles of several common density separators. In the next paragraphs a few types of typical equipment will be given more attention that are considered characteristic in covering a range of applied principles: dry spirals, the Berrisford separator, tables and a variety of fluidised bed separators.

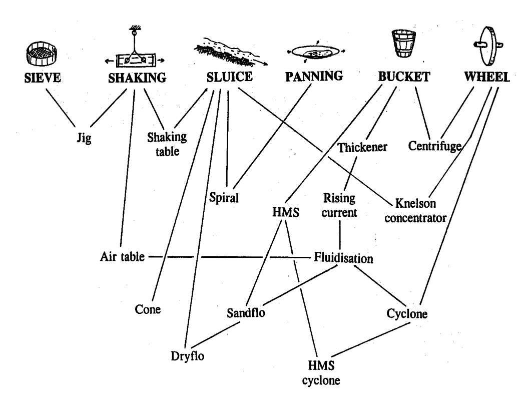


**Figure 1**. Evolution of density separators (Jong, 1999).

This article is focussing on dry separation techniques for coal and in particular dry fluidised sand beds. Dry separators that were successful in the past are reviewed here. They are based on material properties such as friction (Pardee Spiral), resiliency (Berrisford), density (fluidized beds) and a combination of these properties (Air Tables).

### *3.1. Pardee Spiral Separator*

A comprehensive description of the Pardee Spiral is given by Chapman and Mott (1928). The separator was first installed to process anthracite in the USA in 1898. In 1922 there were 4,000 spirals in operation. The coal is fed from a vibrating feeder into inclined feed chutes (Fig. 2). In sliding down the spiral column, the slate particles, because of their high coefficient of friction, do not accelerate but slide down near to the axis. The coal particles on the other hand, acquire an increasing velocity and, as a result, acquire sufficient centrifugal momentum to reach the edge of the spiral surface and pass over into a separate collector. Spirals require an efficiently sized feed, the usual size fractions are 1-2 mm, 2-4 mm, 4-6.5 mm and 6.5 – 10 mm. For these size ranges the capacity for one spiral varies from 6 – 12 tons per hour.

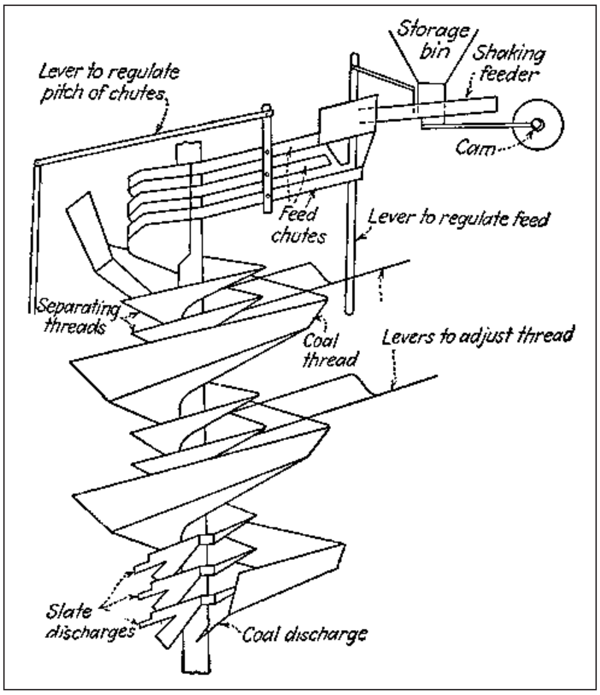


**Figure 2**. Section of the Pardee Spiral Separator (Chapman, 1928).

### *3.2. The Berrisford Separator*

The Berrisford separator is based on the difference between coal and its impurities in resiliency, coefficient of friction, and shape. The coal and shale, 1.0-3.5 cm in size, with a capacity of 15 tons per hour, is pushed off a horizontal step onto an inclined sliding plate. Coal particles have a tendency to bounce along the plane and to gain speed, while shale particles are less resilient and slide slowly down the plane. Shale particles reaching a gap in the plane fall through, whereas the coal particles are moving rapidly and jump across it.

From the literature we learn that the result product has to be corrected by hand-pickers (Chapman, 1928). Certainly, the hand pickers cannot be allowed today to make corrections of the machine output as it was practised in the past. Nevertheless, the machine presents a low cost means of processing with a simple construction, having only a few moving parts.

A recent study carried out at Delft University of Technology to the separation fundamentals of friction and bouncing properties may be of use for eventual further study to the Berrisford separator (Beunder, 2000).

### *3.3. The Air Table*

Pneumatic separation with air tables, is found in many patents dating back as far as 1850 which cover early attempts to separate materials of varying specific gravity or of different shape by means of air (Payne, 1913; Sutton, 1919; Delamater, 1927). Until 1930 hundreds of patents covering this art have been issued, they may be roughly classified into four general groups, as follows:

1. Stationary devices with pulsating air currents. The separating surface is usually riffled and air is supplied by fans or compressors. This group also includes air jigs, which have been used rather extensively.
2. Stationary devices with continuous air currents. These machines submit the material to a continuous current of air, either horizontal or vertical. E.g. chaff is blown from wheat by such a device.
3. Reciprocating or vibrating devices with pulsating air. A small group in which the pulsating air is supplied by a fan and some motion provided in the separating surface to move the stratified material to various discharge points.
4. Reciprocating or vibrating devices with a continuous air supply, e.g. the American Pneumatic Separator (Fig. 3).

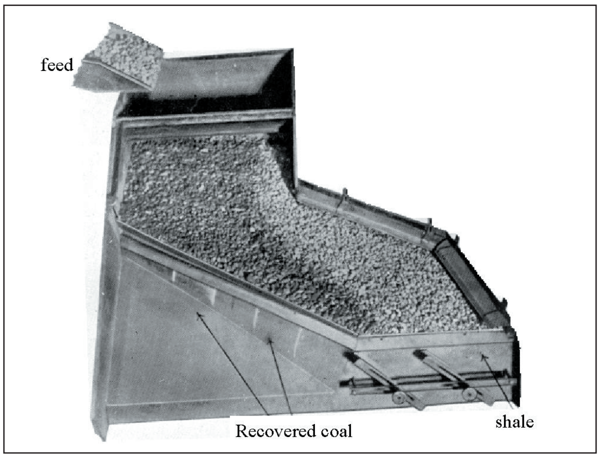


**Figure 3**. The American Pneumatic Separator (Chapman, 1928).

The last group was in 1924 by far the most important and developments have been along this line until the present day. Examples of this type of separator can be found in the agriculture, recycling and minerals sector. All of the above groups involve the stratification of material by air and include often a combination of other principles, such as friction, shape, resiliency and vibration. A similar air separator, type Berry table, was until 2003 in use in the coal preparation plant of Dr Arnold Schäfer GmbH in Saarwellingen, Germany.

The size range of the feed of a machine has to be within a 2:1 ratio. Size ranges can be handled from 2-4 mm up to 5-10 cm, with a capacity ranging from 12 – 60 tons per hour respectively.

### *3.4. Dry fluidised bed separators*

The fluidised bed provides an environment having a density between the densities of the materials to be separated, so that the less dense particles will float on the top of the bed and the heavier ones will sink through it. Early developments were associated mainly with coal cleaning operations. Presently systems are applied in the field of minerals, agriculture, non-ferrous scrap and polymers. From the literature a number of important patents and publications on the subject of dry fluidised sand separation are described.

Three types of fluidised bed separators can be identified:
1. The Yancey and Frazer separator (Chapman, 1928).
2. Two separators developed by Warren Spring Laboratories: an inclined bed separator and a sluice box (Douglas, 1966),
3. The rectangular trough separator (Eveson, 1968; Jong, 1999) and the circular trough separator (Lupton, 1989).

3.4.1. The Yancey and Frazer separator

In 1926 Frazer and Yancey (Frazer, 1926; Chapman, 1928), devised a method to effect a separation of coal and refuse by fluidised sand, with a bulk density of 1.45 g/cm$^3$. Coal floats across the containing vessel; refuse, because of its greater density, sinks through the fluidized sand mixture. River sand was employed. The process is simple, and, if the practical difficulties can be overcome in a large-scale plant, is attractive because of its ability to deal with an unsized (1 – 5 cm) feed.

3.4.2. The inclined bed separator

This separator consists of an inclined vibrating trough with a porous base filled with dry sand. Mixtures are added to the sand. Excess sand with floating particles overflows the separator at the weir side end. The sinking particles are transported from the bottom to the other end of the incline by vibration. The selection and sizing of media is determined primarily by the "cut" densities and by other requirements such as medium cleaning systems. Feed sized between 7.5 cm and 0.6 mm can be treated effectively in fluidised bed separators by adjusting operational techniques to suit the size of the feed. This type of separator was developed by Warren Spring Laboratories (Douglas, 1966).

A second separator developed by this institution is the sluice box or Dry Flow separator. This separator consists of an inclined rectangular trough through which dry sand is flowing. Sometimes the trough is pinched at the end. The mixture is added to the sand and stratifies in a heavy and light fraction. By means of a splitter or knife the fractions are separated.

3.4.3. Trough separators

Another trough separator similar to Fig. 4 is applied for the sorting of minerals and the sorting of agricultural products (Zabeltitz, 1972; Zaltzman, 1982). They are also in use for the separation of non-ferrous metal scrap (Farley, 1995; Jong, 1997). A circular design consisting of a horizontal vibrating trench offers a convenient solution for the sand circulation and the sorted material is de-sanded during passage on inclined screens (Lupton, 1989). For scrap applications the sand is replaced by zircon or hematite in order to float aluminium.

## 4. Evaluation of dry separators

In conventional wet coal preparation, as practised in the majority of operations in Europe, the majority of coal is present as >5 mm solids and is separated by means of jigging or heavy medium separation (HMS). Dry separation must compete with both, in order to successfully replace wet processing, with regard to the restrictions mentioned. Of the described techniques, dry float sink separation in fluidised sands comes close to jigging. It is effective within a wide size range, so avoiding the need of excessive sizing, and could be designed to have a high enough throughput. At first sight the application of a dry fluidised bed as heavy medium for coal – ash separation theoretically promises a result that is close to jigging, however this is not always obtained in practice. This is due to poor control due to misunderstanding of the separation mechanism (Jong, 1997). Besides, effect of moisture and control of the process must be investigated in greater detail. Only after this has been established can dry separation be competitive relative to conventional wet processing.

Investigations recently carried out at Delft University of Technology therefore were focused on optimisation of separation parameters and modelling of the process specifically for coal ash mixtures, with the objective of obtaining the purest possible >5 mm coal fractions with dry processing. The effect of variable surface moisture content was investigated, because in practice it will be of particular relevance for operations near actual mines.

## 5. Investigations on dry fluidised bed float-sink performance for the density separation of 20-30 mm coal

A pilot sized separator similar to the design of Eveson (1968) was constructed and used for the experiments (Fig. 4). The separator consists of a horizontal rectangular vibrating box; 160 cm long, 20 cm deep and 15 cm wide. The coal/shale mixture (F) is added at one end (***b***) and the separated fractions leave at the other end of the box passing a splitter (***d***) via extracting openings (***e*** and ***f***). Through the porous bottom (***c***) compressed air is flowing to fluidise the sand giving it the required density to separate the coal particles from the shale particles. The heavy and light fractions (H+M and L+M) are transported by vibrating feeders (***e***, ***f***) to two revolving screens (not shown) to separate the sink and float from the sand. The sand is re-circulated to the separator via bunker ***a***.

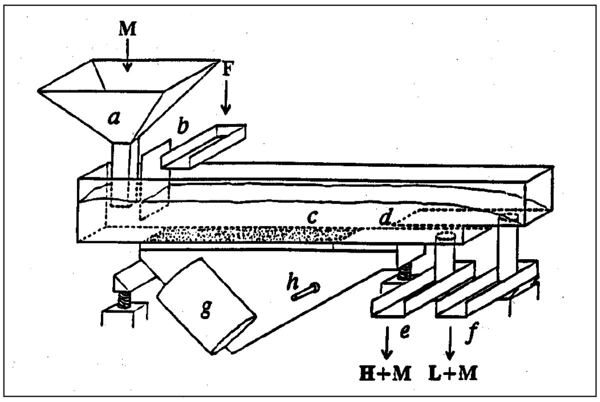


**Figure 4**. Pilot scale fluidised bed separator of Delft University of Technology. F=feed inlet, a=feed bin of sand medium, b=feed vibrator of coal/shale mixture, c=porous bottom, d=splitter of sink and float, h=pressurized air inlet, g=vibration motor, e=sink fraction outlet, f=float outlet. H+M=high density materials with sand medium, L+M=low density materials with sand medium.

### *5.1. Experiments performed with the separator*

Experiments were conducted with variations in the air velocity, the composition of the input and the moisture content of the input. All other variables were kept constant such as machine dimensions, type of sand, vibration, splitter position. The following settings were selected:

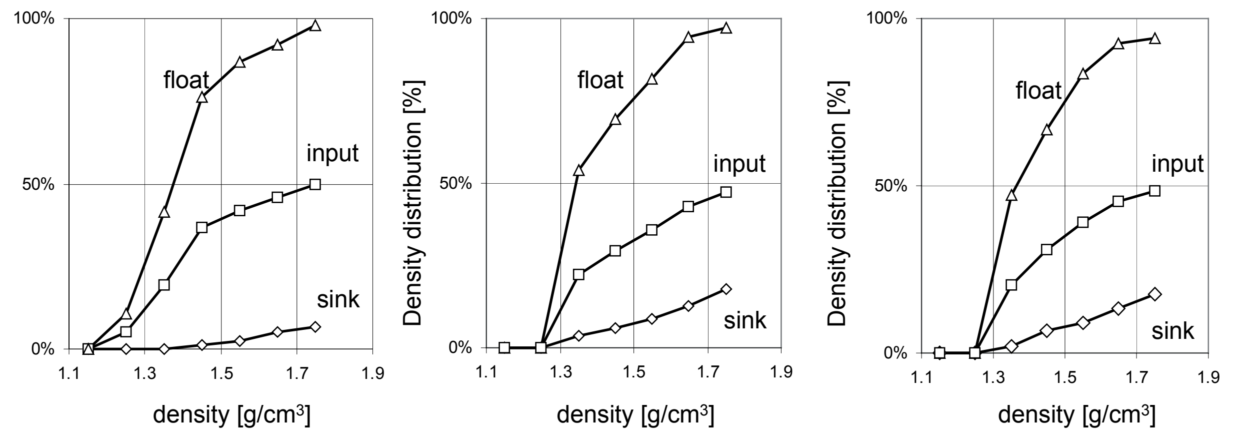
- Superficial velocities of the fluidising gas: 5.80, 5.93, 6.05, 6.42, 6.54, 6.67, 6.91 and 7.16 cm/s (Fig. 5). An increasing velocity causes the bed to expand giving a decreased separating density.
- Part of the tests is performed with dry and dust free coal and shale mixtures. Another part is performed with mixtures of coal and shale that have a surface moisture content of the feed of 5% and in addition adhered with 5% dust (Fig. 6).
- Distribution of coal and shale in the feed (Fig. 7). Different input compositions have been used: a high content of coal (90% coal and 10% shale), an equal share of coal and shale (50%/50%) and a low content of coal (10% coal and 90% shale).

Experiments were carried out with screened and separated coal and shale products provided by the Dr Arnold Schäfer coal preparation plant in Saarwellingen, Germany. The analysed fraction has a size range of 20-30 mm. From this screened fraction, samples were prepared for the experiments. The moisture content of the input mixture of coal and shale was around 2% total moisture, this except for the experimental case of deliberately added moisture to the mixture, in this case the moisture content was around 5%. The sand circulation during the experiments was kept constant at around 7 tonnes per hour while the separation of coal and shale is performed with a capacity ranging from 350-6500 kg per hour for a 15 cm wide pilot sized separator. The sand employed is river sand with a $d_{50}$ of 220 micron. Instead of sand also zircon, hematite or magnetite could be used. Sand, however, is a low cost material with large availability.

For a one meter wide separator in theory a maximum capacity of 40 tons per hour could be reached. In practice a capacity of 20 tons per hour with acceptable results would be possible.

### *5.2. Influence of the air flow rate*

Fig. 5 shows a selection of three tests from a range of experiments performed with different flow rates through the sand bed. The recovered float and sink fractions are analysed with a set of sodium polytungstate liquid solutions with density increments of 0.1 g/cm$^3$. Fluids have been used from a density of 1.2 g/cm$^3$ up to a density of 1.8 g/cm$^3$, material with a higher density is considered to



a) air velocity 6.54 m/s

b) air velocity 6.91 m/s

c) air velocity 7.03 m/s

**Figure 5**. Experiments with coal mixtures (50% coal and 50% shale as input), for three air velocities: a) 6.5m/s and b) 6.9 m/s and c) 7.0m/s. Size of coal and shale: 20-30 mm.

be shale with a density of 2.6 g/cm$^3$ and is not included in the figure. The upper line in the graph represents the cumulative percentage of floating material, predominantly coal; the middle line represents the input mixture calculated from the float and sink fraction, and the lower line represents the sink fraction. The data presented are collected after drying the material at 35 °C. The figure shows that this type of bituminous coal contains a range of different densities from 1.3 to 1.7 g/cm$^3$ which indicates a poor degree of liberation of the coal. With an increasing flow rate, an increasing amount of less dense coal will migrate downwards through the fluidized bed and report in the sink. Consequently the sink fraction will increase in coal grade (Fig 5b and 5c).

In this set of experiments the variation of the flow rate has been tested with dry coal and shale mixtures of 20-30 mm.

### *5.3. Influence of the moisture content of the mixtures on the separation*

In practice moist run-of-mine coal picks up a considerable amount of fine dirt, typical values are around 5%. In the experiments this situation was imitated. Typical moisture values are 3.9-4.3%.

To prepare a sample, dry and dust-free coal and shale (2-3 cm) are mixed with slurry of fine coal and shale (<1 mm). Excess fines and water are shaken off with a vibrating screen, the remaining material is used for the tests. This material typically holds 4% moist and 5% dirt average. The moist and dirty coal-shale mixture then is processed with the sand separator. The coarse and moist particles upon immersion in the fluidized sand, instantly are wrapped with a sand layer. The particles after separation are screened to remove the sand with a revolving screen (punched round opening of 2 mm), most of the moist sand wrap is also shaken off and returned to the sand cycle. To make up for the sand loss new sand has to be supplied continuously.

One would expect that after a while the processing sand would get moist and contaminated itself from the moist and dirty coal. This, however, has not been observed. The air flow has the additional function of drying.

Part of the fine dirt gradually will get mixed up with the sand contaminating it after a few hours of processing. Disturbance of the separation is, however, not observed. If contamination with shale becomes a problem, dirty sand can be replaced continuously by a bleed. The fine shale has the same density as the sand and will get mixed with the fluidizing sand, fine coal on the other hand floats on top of the bed in a fine layer of less than one mm. From time to time this layer has to be skimmed.

A poor coal quality with small losses of coal in the sink is achieved with an air flow of 6.4 m/s (Fig. 6a). A considerable loss of coal in the sink is achieved with an air flow of 7.2 m/s (Fig. 6b). The optimum air-flow is between 6.4 and 7.2 m/s for moist and dirty mixtures. Contrary to wet processing the adhered coal dust ends in the coarse product.

### *5.4. Influence of the input composition*

The input composition has a great influence on the separation result (Fig. 7). The experiment shown in Fig.7a with a rich coal mixture results in a float fraction with almost pure coal with a maximum density of 1.7 g/cm$^3$. Some coal with a density larger than 1.5 g/cm$^3$ appears in the sink (Fig. 7a).

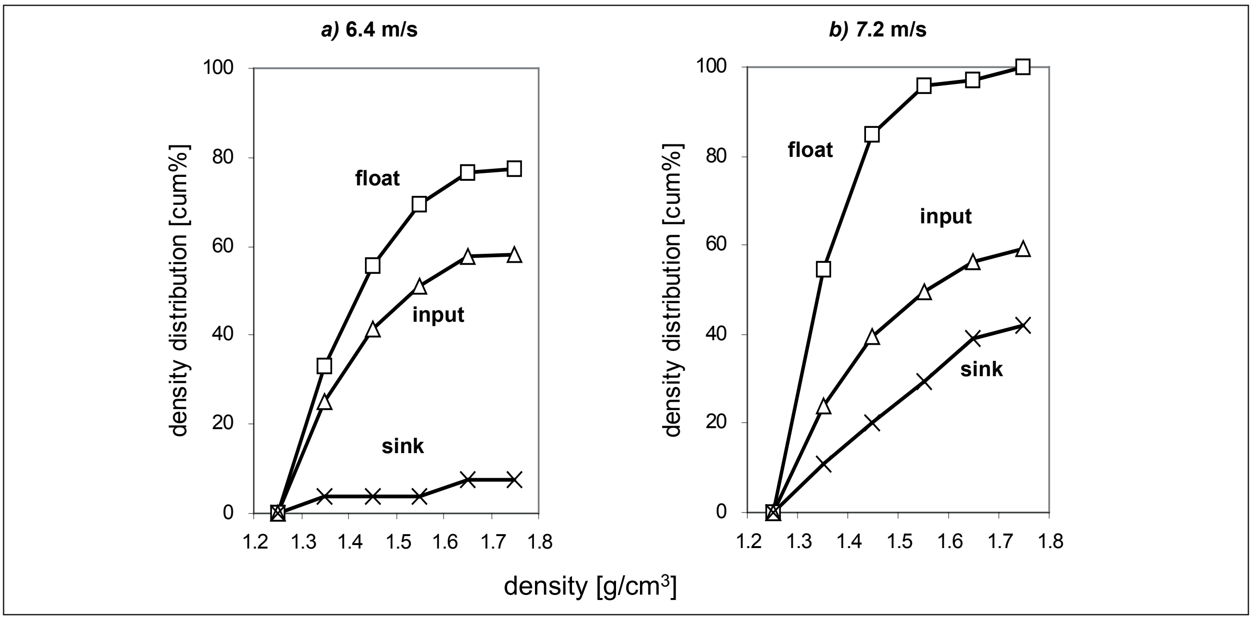


**Figure 6**. Experiments with moist and dirty coal mixtures (50% coal and 50% shale as input), for two air velocities: a) 6.4m/s and b) 7.0 m/s. Size of coal and shale: 20-30 mm. The moisture content is 4.1% average and the adhering dirt 5% average.

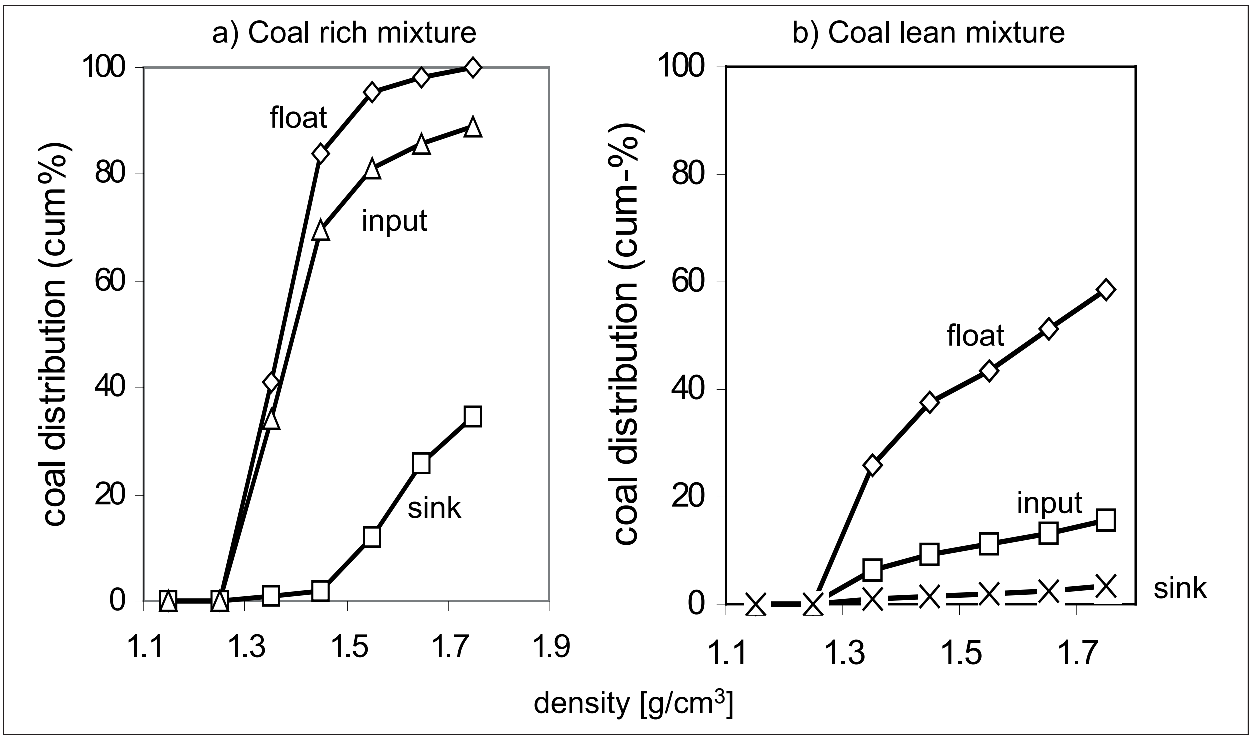


**Figure 7**. Influence of composition. Two examples of a range of experiments are shown a) with coal-rich mixtures of 90% coal and 10% shale and b), coal-lean mixtures with 15% coal and 85% shale. Particle size: 20-30 mm. Air velocity for a) and b): 6.5 cm/s.

The same experiment performed with a lean mixture (Fig.7b) results in a sink almost free of coal. This resembles the result of Fig. 5a. A lean coal mixture results in a float with a poor quality.

The Dr Arnold Schäfer plant in Saarwellingen is employing dry separators. The fluid bed separator product of Fig 7b is similar to the product of the German plant. The high ash product from this separation is suitable as a feed to an electric power plant. With slight adaptations in the air flow the product composition can be improved.

### 5.5. Partition curves.

For the experiments performed partition curves have been constructed. Examples of such curves are given in Fig. 8. The construction of these curves combines the input data with the results of sink and float products into one single curve instead of three. This curve characterises the experiment with one decisive parameter: the $E_p$-value [1].

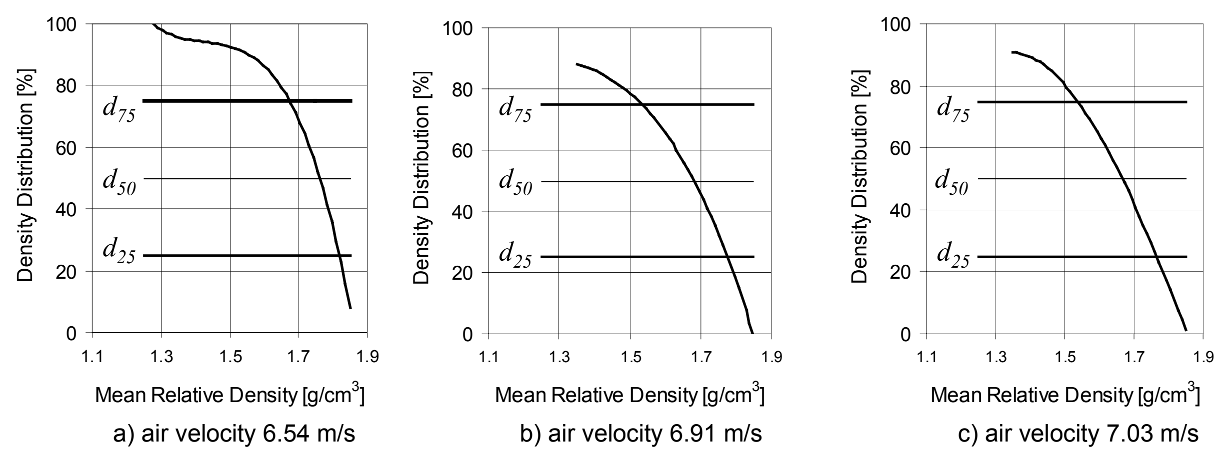
$$E_p = (d75 - d25)/2 \qquad [1]$$

The average $E_p$-value calculated from the performed dry fluidized bed tests was determined at around 0.1, this value is close to that found for wet jigging. The $E_p$-value for wet heavy medium separation is 0.01-0.05. The lower the value, the steeper the partition curve, and the better the separation.

From each of the set of three curves in a), b) and c) of Fig. 5 a single partition curve can be constructed (Fig. 8a, b and c). From the partition curve an Ep-value of 0.09 (a) 0.13 (b) and 0.12 (c) respectively, is calculated. The flow rate shown in Fig. 5 and 8 is increasing from 6.5 m/s in a) to 7.0 m/s in c). The separation density at $d_{50}$ is 1.74 (a), 1.68 (b) and 1.67 g/cm$^3$ (c) respectively.

### 5.6. Conclusions experiments

- Separation results are comparable to conventional wet jigging. The $E_p$-value (probable error) for fluidized bed separation has an average value of 0.1, which is close to wet jigging.
- Separation results are similar to those of the Dr Arnold Schäfer plant in Germany.
- With variations in the air flow a coal product of different composition can be produced.
- With sand as a separation medium acceptable results are achieved.
- Moisture causes sand and dirt to adhere to coal, but this hardly affects the separation.



a) air velocity 6.54 m/s b) air velocity 6.91 m/s c) air velocity 7.03 m/s

**Figure 8**. Partition curves of the separation of coal and shale with increasing air flow rates. The $d_{50}$ value is 1.74 (a), 1.68 (b) and 1.67 (c) resp. and the $E_p$-value is 0.09 (a), 0.13 (b) and 0.12 (c) respectively.

## 6. Discussion

High capacity, low maintenance, low investment costs and sharp, constant separation results at variable feed and moisture make dry separators competitive with wet processing. Available literature data, supplemented with the additional investigations recently carried out, suggest that these restrictions can be met by taking sufficient technological measures. In the case of dry float-sink separation in a sand fluidised bed, special attention must be given to effectively control the process and reduce sand loss. In this respect it should be noted that a less sharp separation in some cases is justified since the total processing costs are considerably lower or when no wet alternative processing can be carried out. Thermal coal is a relatively low cost commodity and cost savings naturally have priority above obtaining the highest possible recoveries.

At Delft University investigations take place to apply dual-energy X-ray transmission imaging for on-line ash and size monitoring, parallel to the mentioned fluidisation experiments. The objectives are to provide on-line data for controlling crucial separator settings and to enable after-treatment of separated coal to high purity using pneumatic automatic sorting. Part of this work is reported in a separate contribution to the 5th European Coal Conference held on 17-20 September 2002 in Mons, Belgium (Jong, 2003).

## 7. Acknowledgements

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