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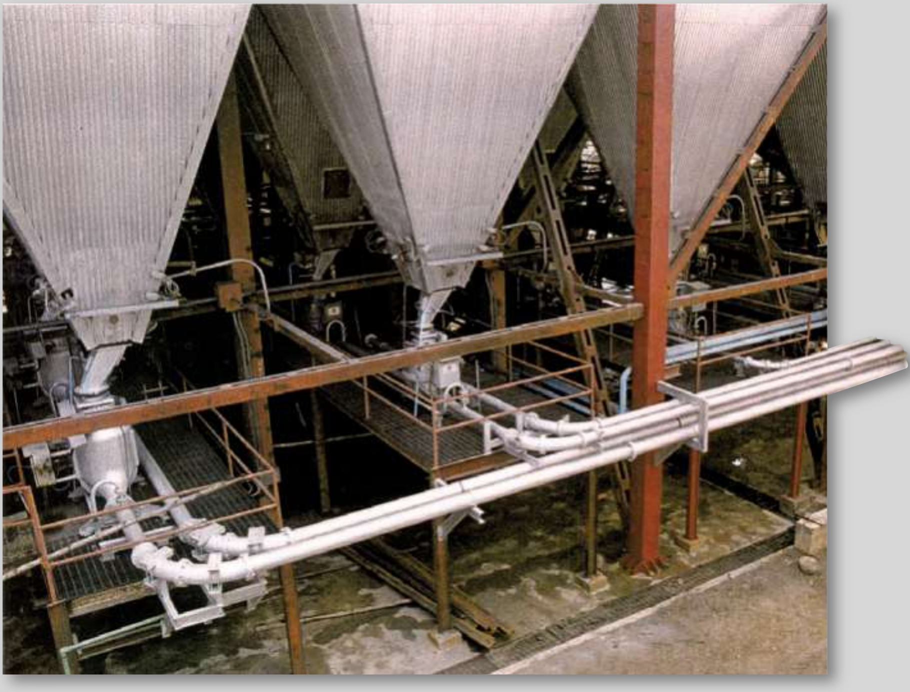
# Pneumatic Conveying Systems

Design, Selection and Troubleshooting with Particular Reference to Pulverised Fuel Ash



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David Mills / V. K. Agarwal
Pneumatic Conveying Systems

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# Pneumatic Conveying Systems

Design, Selection and Troubleshootimg with Particular Reference to Pulverised Fuel Ash

2nd edition

Vogel Buchverlag

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After gaining a First Class Honours Degree in Mechanical Engineering Dr. Mills worked in the area of Thermodynamics and Heat Transfer, both in industry and academic. In 1973 he turned his attention to Bulk solids Handling and under took a Ph.D. programme on the erosive wear of bends in pneumatic conveying system pipelines. He has been specializing in the area of pneumatic conveying ever since, first at the University of Greenwich, then as Professor of Bulk Solids Handling at Glasgow Caledonian University. For the last four years he has been operating as an independent consultant. He was commissioned by the Department of Trade and Industry in the UK in 1982 to produce a general Pneumatic Conveying Design Guide and this is now recognized as the definitive book on the subject. He has also written some 150 journal articles and conference papers on various aspects of pneumatic conveying and has lectured widely on the subject around the world. Dr. Mills has been working with Dr. V.K. Agarwal on a regular basis for the last 20 years.

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# FOREWORD

Fly ash conveying tends to be a rather neglected subject area, particularly with regards to books. Such neglect is probably due, in part, to the near zero value of the commodity. Having worked in this particular area for many years, however, the authors have recognized a definite need for such a book. System design is not straightforward and errors in component specification tend to be made on a regular basis. A particular problem with fly ash is that that material is automatically graded in the collection hoppers in boiler plant, and different grades of fly ash can have very different conveying characteristics.

The efficient handling of fly ash, however, is essential for the smooth running of the associated power plant. If ash accumulations in boiler hoppers are not cleared, for any reason, the boiler plant will generally have to be shut down and the financial consequences can be quite considerable. Fly ash handling almost represents an industry on its own, with a multitude of companies involved in the design, installation and operation of conveying equipment. In India alone, fly ash generation has already reached 112,000,000 tonne/yr and is set to continue rising at a high rate into the foreseeable future. Similar trends are observed in China, where the coal based power plants are being added on a continuous basis. In emerging economies, such as Indonesia and Brazil, coal fired power stations are also being built at a rapid rate, and in countries such as South Africa and Poland coal still has to be the fuel of choice since gas, oil and nuclear are not options, despite the perceived problems of global warming.

Much confusion exists around the definition of dilute and dense phase conveying and so this is an issue that is addressed in detail. In general, in a conventional positive or negative pneumatic conveying system, coarse grades of ash can only be conveyed in dilute phase, and so high values of conveying air velocity must be employed, with the ash conveyed in suspension in the air. Fine ash, however, can usually be conveyed in dense phase, non suspension flow, and with very much lower conveying air velocities but this capability is dictated very much by the concentration of the ash in the air, the pressure drop available and the conveying distance.

The critical design parameter in any pneumatic conveying system is the conveying line inlet air velocity. With different grades of the same material requiring different values of this velocity, considerable care must be exercised in the design and specification of the plant and components if different grades are to be conveyed in a common system. An added problem is that the different grades of fly ash are generally at different temperatures and this adds to the complexity of specifying air requirements and calculating air velocity values. Yet another problem is the fact that fly ash is generally a very abrasive material and so component specification must take this into account also. Pneumatic conveying of the bottom ash is gaining much ground and that means another grade of coal ash in terms of the temperature, particle size distribution and the conveying performance in the pipeline.

In systems where fly ash is drawn from ash hoppers to intermediate silos by vacuum conveying, and is then conveyed onward by positive pressure to bunkers for disposal, further problems can result in this onward conveying if a mix of both fine and coarse ash has to be handled. Emphasis is given to both system design and system operation in the book, and so problems of this nature are considered in two ways. For a new system the conveying variables are highlighted so that they should be taken into account in the system analysis and design procedures. For existing systems two chapters are devoted specifically to troubleshooting and numerous equations are presented throughout the book that can be used to check operating parameters.

Stepped pipeline systems are a design feature that is given prominence, and this applies to both positive pressure and vacuum conveying systems. Several case studies are included to illustrate the design procedures for both fine and coarse ash, and these are used further to illustrate the basic fact that there is no one fixed set of design and conveying parameters for a given conveying system. An infinite combination of air supply pressures and pipeline bores is generally capable of meeting any conveying duty, limited only by the availability of standard pipeline bores and the problem of accommodating very high air supply pressures. It is to be recommended that alternative designs should be considered for any system and that these should be evaluated in terms of capital costs and running costs. By this means a true economic cost comparison can be made, in which it should also be possible to include maintenance costs.

Much of the conveying data presented in the book was obtained by students running pneumatic conveying test facilities. This is why such high values of solids loading ratio and low value of conveying air velocity have been achieved in much of the work presented. The authors often state in short courses that "anyone can convey fine fly ash" and cite the case of our many students and their results in order to encourage delegates attending. From our experience with coarse ash, and visiting innumerable power plants where the ash is also at a high temperature, however, we do recognize the many problems and we hope that this book will help in gaining a clearer understanding of the issues, the design process and the operating problems.

Dr. David Mills
Dr. V.K. Agarwal
January 2009

# CHAPTER 1

# INTRODUCTION

# CONTENTS

# BACKGROUND

Millions of tonnes of coal are burnt in thermal power plants across the world. Thermal power constitutes more than half of the world's electric power generation [Ref 1]. The quality of the coal used varies widely from one country to another. It can vary with the location of the coal mine, and in some cases the quality of coal can vary between the upper and lower seams in a mine. This variation can be in terms of both the calorific value of the coal and the quantity of unburnt residue produced when it is burnt in a boiler. The quantity of ash generated, and its collection at various locations, is influenced by the ash content of the raw coal, the boiler operating conditions, the excess air used in the combustion process, and the soot blowing operations.

Millions of tonnes of ash are thereby produced and the ash can have a wide range of properties as a consequence, both in terms of chemical composition and particle size. It is important, therefore, that any system built to convey this ash should be reliably designed to take account of the properties of the conveyed material. With fly ash having little or no commercial value, however, such conveying systems are not always given the consideration that they require. A poorly designed conveying system can result in repeated plant shut down, with a very significant loss in revenue. With such a high production rate of ash it is essential that the material is reliably and efficiently removed from the plant.

## Ash Generation

The coal in the "As Received" condition is first pulverised in grinding mills to obtain Pulverised Fuel (pf) or Pulverised Coal. During the burning of the coal, glassy droplets of ash are produced. Some of these particles impinge on the furnace wall, and at high temperatures the particles can fuse together to form deposits of slag. Build up of thick layers of ash on a furnace wall increases resistance to the heat transfer process, thus reducing the thermal efficiency of the boiler. In order to minimise the effects of the ash build up, these deposits are periodically blown off by soot blowers. The dislodged lumps fall into the ash hoppers at the bottom and this is generally referred to as Furnace Bottom Ash (FBA) or simply Bottom Ash.

### Fly Ash

The finer particles of ash are carried away with the flue gases and get collected at several locations along the flue gas path. This ash is commonly referred to as Pulverised Fuel Ash (pfa) or simply Fly Ash. The coarser fraction of this ash is collected in the economiser, air pre-heater and duct hoppers. The finer fraction, and generally the largest percentage, is collected in the electrostatic precipitator (ESP) hoppers.

The FBA constitutes about 10 to 15 % of the total ash and consists of very coarse particles and large lumps. The remaining 85 to 90 % (fly ash) is generally much finer, typically having a mean particle size varying from about 130 micron in the economiser hoppers to about 20 micron in the ESP hoppers. Figure 1 shows a typical layout of the ash collection points, and approximate percentages of ash collected at each location. The temperature of the ash also decreases as it moves away from the furnace and through the gas passages [Ref 2].

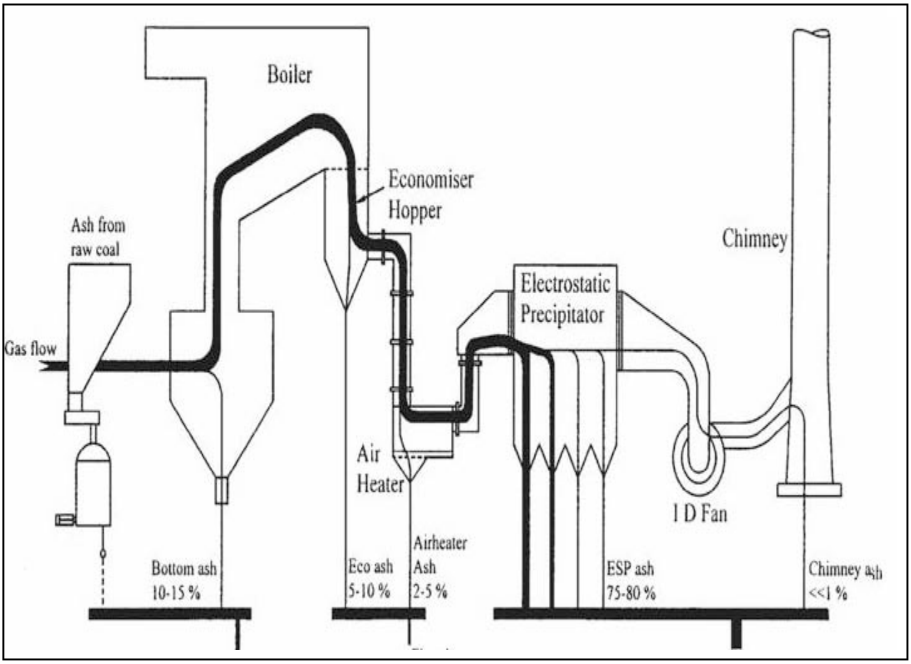



Figure 1: Ash Accumulation Points and Typical Ash Distribution of a Dry Bottom Furnace

The quantity of ash produced depends principally upon the quality of the coal used. It is further influenced by the combustion process in the boiler, and other operating variables, as mentioned above. An inefficient combustion process, for example, may result in a high level of unburnt carbon in the ash produced. Carbon in ash gives it a dark colour, and as a result the ash becomes unsuitable for certain applications. The ash content in superior grades of coal can be as low as 6 to 8 %, but can be as high as 45 % in poor grades.

India, for example, has abundant coal reserves, but the coal has such a high ash content that to produce 55,000 MW of thermal energy, the quantity of coal burnt produces approximately 80 million tonne of fly ash every year [Ref 3]. Proper utilisation, or safe disposal, of such enormous amounts of fly ash is a challenge to engineers associated with power generation. It is, therefore, inevitable that power plant requires an efficient and reliable ash handling system.

## Properties of Fly Ash

It is important that the properties of any material that has to be conveyed should be taken into account, and that any variations in properties that are likely to occur, from any source, are also allowed for. The chemical composition of coal, and hence of the resulting ash, will vary both globally and locally. This will also influence particle and bulk density. Particle size will vary with respect to the location of the ash hopper on the boiler plant, as well as the air flow settings on the coal grinding mills. Particle shape will be influenced to a certain extent by changes in the combustion process.

## Typical Ash Composition

Silicon oxide and aluminium oxide are two major components in the chemical composition of fly ash. The percentage of silica can be as high as 65%, and alumina can vary between about 15 and 30 %. Both alumina and silica are very hard materials, having a hardness value close to 8 on the Mohs scale of hardness. It is because of the high concentration of these constituents in fly ash that it is very abrasive, and can cause damage to all surfaces into which it comes into contact, whether by abrasion or impact. The composition of a typical fly ash is given in Table 1.

| Oxides | As Received | Non Mag. |
|---|---|---|
| $SiO_2$ | 65.1 | 65.0 |
| $Al_2O_3$ | 25.1 | 17.6 |
| $Fe_2O_3$ | 4.2 | 1.8 |
| CaO | 1.4 | 4.5 |
| MgO | 0.4 | 2.0 |
| $TiO_2$ | 1.1 | N.A. |
| $Na_2O_3$ | 0.5 | N.A. |
| $K_2O$ | 1.8 | N.A. |

Table 1: Chemical Composition of a Typical Fly Ash

In some cases the ash may also contain trace elements, such as chromium, boron and arsenic. The ultimate safe disposal of such ashes may require additional measures to be taken to prevent contamination of the soil.

## Size Distribution and Temperature

As the flue gases pass through the boiler ducting, ash is collected at several locations along its route. The particle size of the fly ash decreases as the distance of the collection point from the boiler combustion zone increases. The ash is first collected in the economiser hoppers, and then the air pre-heater hoppers, before it enters the series of electrostatic precipitator hoppers. ESP's charge the dust particles and use electrostatic attraction to remove approximately 99.5 % of particles from the flue gas. About 85% of the total ash carried with the flue gas is collected in the ESP hoppers.

The average or mean particle size of the ash particles collected in the economiser and air pre-heater hoppers is about 100 microns. The size of the ash particles collected in the ESP hoppers, however, is much finer. Within the various zones of the electrostatic precipitator, ash collected in the initial row of hoppers, in the direction of the gas flow, is of a higher average particle size as compared with the ash collected in the last row of hoppers. Although the particle size of the ash collected in the ESP hoppers will vary from plant to plant, typical values of the particle size of the ash collected in the ESP hoppers of a typical 210 MW generating unit are given in Table 2. Typical values for the temperature of the ash are also given for reference.

| Ash Collection Point in Boiler | Economiser | Air Pre-Heater | Electrostatic Precipitator | Stack |
|---|---|---|---|---|
| Ash Particle Size | Less than 750 μm<br><br>Mean Particle Size of 120 μm | Less than 750 μm<br><br>Mean Particle Size of 100 μm | Larger than 100 μm = 2 to 20%<br>Less than 100 μm = 80 to 98%<br>Less than 80 μm = 75 to 97%<br>Less than 60 μm = 70 to 96%<br>Less than 40 μm = 60 to 90%<br>Less than 20 μm = 40 to 80%<br>Less than 10 μm = 25 to 65%<br><br>Mean particle size of 25 μm | Very Fine |
| Ash Temperature | 300 $^{o}$C | 250 to 300 $^{o}$C | 130 $^{o}$C | Less than 100 $^{o}$C |

Table 2: Particle Size Distribution and Temperature of Ash Collected at Various Locations

Bottom ash consists of large lumps which are generally crushed to a smaller size before being mixed with water to be disposed of in slurry form.

## Shape of Fly Ash Particles

Since ash particles are produced as glassy droplets, as a result of combustion in the boiler, the majority of fly ash particles are spheroidal in shape. Some particles of ash were observed under a microscope and a photograph is presented in Figure 2. It will be observed from these slides that the particle shape can also vary due to agglomeration and fusing of particles.

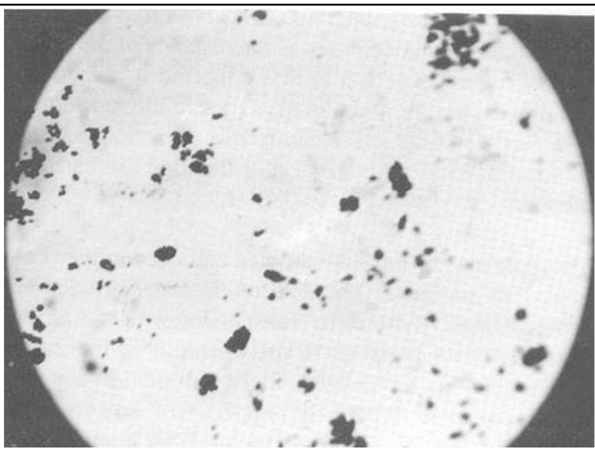


Figure 2: Photograph of Particles in a Typical Sample of Fly Ash X 100 magnification

## Particle and Bulk Density

In the case of materials that have to be handled in a large quantity, bulk density can be an important variable to consider. Since bulk density takes into consideration the particle density and voids in bulk storage, it is a useful parameter for the sizing of various system components. Particle density will influence the slip velocity when the material is conveyed pneumatically through pipelines in two phase flow. It is important, therefore, to have an idea of the typical range in which the particle density and bulk density of fly ash can vary. Most fly ashes have a bulk density of about 720 kg/m$^3$ and a particle density of around 1800 kg/m$^3$.

## Ash Collection Hoppers

Since close to 75 % of the total ash produced in the combustion process is collected in the ESP zone, it is necessary to consider the layout of these ash collection hoppers. The electrostatic precipitators have several fields and each field has a number of collection hoppers. A 210 MW generating unit will typically have six fields and eight hoppers in each field, thus making a total of 48 ash collection hoppers. A sketch showing the layout of a typical group of ESP hoppers, and the direction of the gas stream, is given in Figure 3.

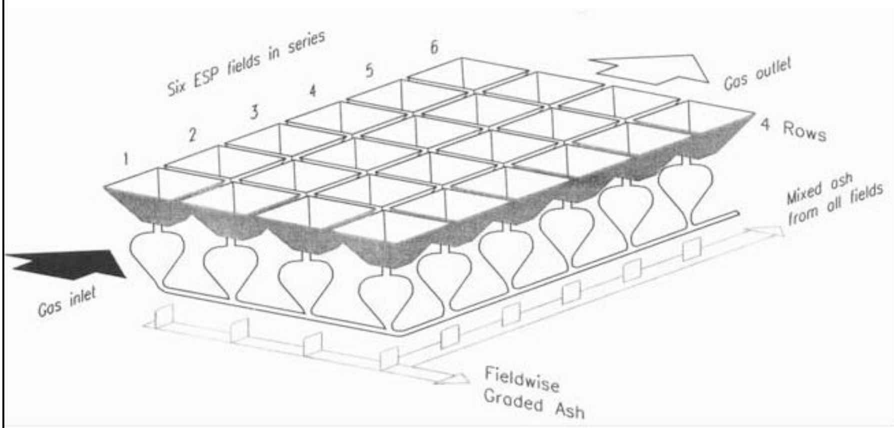



Figure 3: Typical Arrangement of Electrostatic Precipitator Ash Collection Hoppers

The first field hoppers have the highest ash collection rate, which may vary between 70 and 80 %. The rate of ash collection in subsequent fields decreases in similar proportions. As a result the ash collected in the hoppers of field 3 and onwards is very minimal.

If, during a failure, field 1 is not operational, the field 2 hoppers would have the same collection rate as the field 1 hoppers in normal operating conditions. The capacity of the ESP hoppers is generally selected so that they are capable of storing as much ash as is generated in 24 hours of plant operation. The design of the ash handling system has to consider the time cycle for the ash evacuation, keeping in view the differences in ash collection rate in the various hoppers.

### Off-Loading Arrangements

The removal of ash from the ESP hoppers can either be in a direction parallel to the gas flow, as shown in Figure 3, or across the direction of the gas flow. In the first case hoppers of various fields will be connected to each other so that the ash collected in the receiving silo will have a mixture of coarse and fine ash. In the latter option, the hoppers of a particular field will be interconnected thus making it possible to keep the coarse ash of the initial two fields separate from that of the very fine ash of subsequent fields.

Fly ash from the last few fields is generally preferred whenever it is required for use as a cement substitute in the construction industry. In the case of the cross direction ash evacuation arrangement, however, the loading on the ash removal system would be non uniform due to the large differences in the ash collection rate in the hoppers of the various fields. This factor must be taken into consideration when designing the ash removal system for such an arrangement. The choice of system depends largely upon the end utilisation of the ash and the ESP plant layout.

## Ash Removal Systems

The selection of an ash removal system depends upon the nature of the ash, the quantity of ash to be handled, and if the ash has to be graded for the end utilisation. Possible ash removal systems include mechanical, hydraulic and pneumatic conveying systems.

### Hydraulic Conveying

Conventional hydraulic conveying systems are widely used for the disposal of ash into ash lagoons. Ash is discharged from the various ash hoppers, mixed with water and transported through open channels into the ash sump. From the sump the ash is conveyed in slurry form to the ash lagoons, which could be located up to several kilometres from the plant. In countries like India, where ash generation is so enormous, and applications for utilisation not fully explored, slurry disposal of ash is still practised at most power stations. The recent trend is to go in for high concentration (up to 70 % ash) slurry instead of dilute slurry having only 20 % ash content. Such high concentration slurry should result in savings of water, specific power consumption and ash disposal area required.

Environmental problems associated with ash lagoons in many countries, however, are starting to have an impact on the viability of this method of disposal. Legislation is also coming into force in a number of countries which is setting gradually increasing targets for the practical use of fly ash, with the aim of reducing the quantity of ash that has to be disposed of. For most applications the ash must remain dry and so this is also reducing the potential for hydraulic conveying systems.

Pneumatic Conveying

Pneumatic conveying systems offer an ideal choice for the handling of fly ash in dry form. Although in some cases the mixed ash from ash ponds can be conveyed, for most applications it is desirable to convey dry fly ash. Pneumatic conveying systems broadly fall into two categories: the suction system and the pressure system. Air slides can be considered to be an extreme form of pneumatic conveying wherein very high material transfer rates can be achieved by employing the advantage of gravitational flow aided by artificial fluidisation of the material.

Harder [Ref 1] has presented an overview of the systems available to convey fly ash. Figure 4 shows some possible alternatives that can be used for the transportation of ash. Typical values of the conveying parameters associated with these systems are also marked against them. Each system has its own limitations in terms of the conveying air velocity, the maximum achievable pressure drop, distance of conveying, and the concentration, or solids loading ratio, at which the material can be conveyed.

Vacuum or suction type systems generally require a high conveying line inlet air velocity and the maximum permissible pressure drop is typically restricted to about 0.5 bar gauge. These are well suited, however, to situations requiring multiple point pick up of the material, as in case of the evacuation of ash from ESP and other ash hoppers. The distance of conveying, however, is restricted due to the limitation on the pressure drop.

Positive pressure pneumatic conveying systems are now widely accepted for conveying fly ash at power stations. Depending upon the specific application, either dilute phase suspension flow systems or dense phase low velocity systems can be used. Several operating parameters have to be considered in making a judicious choice of the system most appropriate for a given application. The major advantage of positive pressure systems is that since high pressures can be employed for the conveying system, it is possible to convey the material over long distances. A good number of pneumatic conveying systems are in use at power stations where the conveying distance exceeds 1000 m and can go up to 2000 m. A detailed description of these systems, components and design criterion is discussed in the following chapters.

# PNEUMATIC CONVEYING

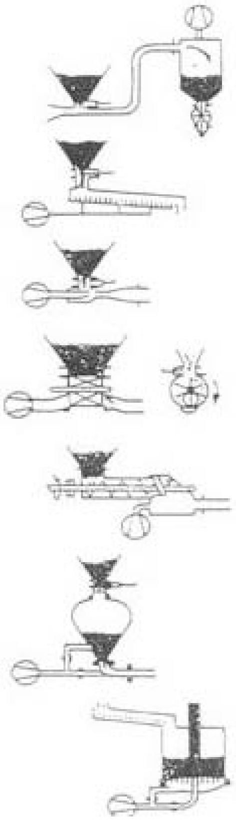
Pneumatic conveying systems are basically quite simple and are eminently suitable for the transport of fly ash and various other materials in thermal power plant situations. The system requirements are a source of compressed air, a feed device, a conveying pipeline and a receiver to disengage the conveyed material and carrier gas. The system is totally enclosed, and if it is required, the system can operate entirely without moving parts coming into contact with the conveyed material. High, low or negative pressures can be used to convey these materials.

## System Flexibility

With a suitable choice and arrangement of equipment, materials can be conveyed from a hopper or silo in one location to another location some distance away. Considerable flexibility in both plant layout and operation are possible, such that multiple point feeding can be made into a common line, and a single line can be discharged into a number of receiving hoppers. With vacuum systems, materials can be picked up from open storage or stockpiles, and they are ideal for clearing dust accumulations and spillages.

**Pneumatic ash removal systems**

**Conveying parameters**



| | $\phi$ kg/kg | $\Delta P_{max}$ bar | $L_{max}$ m | $m_{max}$ t/h |
|---|---|---|---|---|
| Suction Conveyor | 20 | 0.5 | 100 | 100 |
| Airslide | 300 | 0.05 | 100 | 400 |
| Jet feeder | 5 | 0.2 | 75 | 5 |
| Air-lock feeder | 30 | 0.75 | 150 | 40 |
| Screw pump | 80 | 1.5 | 80 | 200 |
| Pressure vessel | 200 | 6.0 | 2000 | 150 |
| Airlift | 25 | 0.5 | 100 Vertical | 100 |

Figure 4: Pneumatic Ash Removal Systems with Conveying Parameters Indicated

Pipelines can run horizontally, as well as vertically up and down, and with bends in the pipeline any combination of orientations can be accommodated in a single pipeline run. Material flow rates can be controlled easily and monitored to continuously check input and output, and most systems can be arranged for completely automatic operation.

Pneumatic conveying systems are particularly versatile. A very wide range of materials can be handled and they are totally enclosed by the system and pipeline. This means that potentially hazardous materials can be conveyed quite safely. There is minimal risk of dust generation and so these systems generally meet the requirements of any local Health and Safety legislation with little or no difficulty.

Pneumatic conveying plants take up little floor space and the pipeline can be easily routed up walls, across roofs or even underground to avoid any existing equipment or structures. Pipe bends in the conveying line provide this flexibility, but they will add to the overall resistance of the pipeline. Bends can also add to problems of particle degradation if the conveyed material is friable, and suffer from erosive wear if the material is abrasive.

## Mode of Conveying

Much confusion exists over how materials are conveyed through a pipeline and to the terminology given to the mode of flow. First it must be recognised that materials can either be conveyed in batches through a pipeline, or they can be conveyed on a continuous basis, 24 hours a day if necessary. In batch conveying the material may be conveyed as a single plug if the batch size is relatively small.

### Dilute Phase

For continuous conveying, and batch conveying if the batch size is large, two modes of conveying are recognised. If the material is conveyed in suspension in the air through the pipeline it is referred to as dilute phase conveying. If the material is conveyed at low velocity in a non-suspension mode, through all or part of the pipeline, it is referred to as dense phase conveying. Almost any material can be conveyed in dilute phase, suspension flow through a pipeline, regardless of the particle size, shape or density.

### Dense Phase

In dense phase conveying two modes of flow are recognised. One is moving bed flow, in which the material is conveyed in dunes on the bottom of the pipeline, or as a pulsatile moving bed. The other mode is slug or plug type flow, in which the material is conveyed as full bore plugs separated by air gaps. Moving bed flow is only possible in a conventional conveying system if the material to be conveyed has good air retention characteristics. Plug type flow is only possible in a conventional conveying system if the material has good permeability.

### Conveying Air Velocity

For dilute phase conveying a relatively high conveying air velocity must be maintained. This is typically in the region of 10 to 12 m/s for a very fine powder, from 13 to 16 m/s for a fine granular material, and beyond for larger particles and higher density materials. For dense phase conveying, air velocities can be down to 3 m/s, and lower in certain circumstances. Because of the fine particle size required to provide the necessary air retention properties, particle density does not have such a significant effect on the minimum value of conveying air velocity in dense phase conveying, as it does in dilute phase conveying.

### Solids Loading Ratios

The solids loading ratio, or phase density, is a useful parameter in helping to visualise the flow. It is the ratio of the mass flow rate of the material conveyed divided by the mass flow rate of the air used to convey the material. It is expressed in a dimensionless form. For dilute phase, maximum values that can be achieved are typically of the order of 15, although this can be a little higher if the conveying distance is short.

For moving bed flows, solids loading ratios of well over 100 can be achieved if materials are conveyed with pressure gradients of the order of 20 mbar/m. For plug type flows the use of solids loading ratio is not so appropriate, for as the materials have to be very permeable, maximum values are only of the order of about 30. Despite the low value of solids loading ratio, however, materials can be reliably conveyed at velocities of 3 m/s and below in plug type flow.

## Recent Developments

Although pneumatic conveying systems have numerous advantages over alternative mechanical conveying systems for the transport of materials, they do have drawbacks, particularly for materials that can only be conveyed in dilute phase. Particle degradation and erosive wear of pipeline bends are particular examples. Because of the high conveying air velocity required, energy requirements are also high.

In recent years there have been many developments of pneumatic conveying systems aimed at increasing their capability for conveying a wider range of materials in dense phase, and hence at low velocity. This has generally been achieved by providing a parallel line along the length of the pipeline, either to artificially create permeability or air retention in the material.

## Ash Conveying

In power generation plant, fly ash is generally collected in hoppers located at various points in the gas flow path. These are typically in the area of the economiser and air pre-heater, within the boiler plant, and in the electrostatic precipitators, prior to discharge of the gas to atmosphere. Particle size tends to decrease with increase in conveying distance through the boiler plant.

### Material Grade

As a result, fly ash can come in a very wide range of size distributions. There is, however, little information available on how the conveying capability varies with the grade, or size distribution, of the material. Ash from an economiser hopper, for example, is likely to be coarse and granular, and as a result it is unlikely that it will be possible to convey the material in dense phase in a conventional pneumatic conveying system. Ash from an electrostatic precipitator hopper, however, is likely to be fine and powdery, and this will generally convey in dense phase and at low velocity in a conventional conveying system.

It is suspected that fly ash taken from either the economiser hopper, or the air pre-heater hopper, would have little or no low velocity dense phase conveying capability. Such ash will be very much coarser and have a much larger mean particle size than precipitator ash. As a consequence the coarser material will have little air retention capability and very poor permeability. Coarse materials such as this can generally be conveyed only in dilute phase in a conventional conveying system. Coarse fly ash will typically require a conveying line inlet air velocity of at least 13 m/s and it is unlikely that the fly ash could be conveyed at a solids loading ratio much higher than 15, even if high pressure air is used for conveying.

### *Ash Collection*

At many power stations, ash is collected from all the hoppers by positive or negative pressure pneumatic conveying systems, or air-gravity conveyors, and is transported to a holding silo close by, where it will get mixed. From here it is generally conveyed pneumatically by positive pressure to reception silos off-site for subsequent disposal. If precipitator ash is mixed with economiser and air pre-heater ash in this way, any grade of material between 'coarse' and 'fine' must be expected for the reception silo conveying system.

## Operational Problems

Pneumatic conveying systems, like any other conveying system, are also prone to certain operational problems. Some of the commonly experienced problems are pipeline blockage, restarting the conveying system in the event of a power failure or plant shut down due to some unexpected reason, and erosion of plant components. Considerable research, however, has been carried out over the last two decades into these problems and any system designer should be able to incorporate precautionary measures at the design stage itself to at least reduce the severity of any such problems.

### Erosion of Plant Components

It was mentioned above that several types of pneumatic conveying system are used for conveying fly ash. In the case of many suction systems, and dilute phase pressure systems, a high conveying line inlet air velocity is generally required. As the flow proceeds through the pipeline, the gas density decreases due to expansion of the gas. This leads to an increase in the velocity of conveying. Depending upon the air pressure used for conveying, very high conveying velocities can be experienced as a result. Silica and alumina, both of which are very hard and abrasive materials, constitute the main components of fly ash.

The impact of such hard particles against any plant surface, especially pipe bends and diverter valves, will cause severe erosion of the surface, leading to its functional failure. If the coal used in a power plant has a low calorific value, and a high ash content, a 210 MW plant could generate as much as 1500 tonne of fly ash every day. The handling of such a large quantity of ash through a pneumatic conveying system can cause severe bend erosion. It is important, therefore, that the design of the conveying system should be based on the lowest possible conveying air velocity, consistent with reliable conveying. Suitable materials of construction for the bends also need to be selected, according to the geometry of the pipe bends employed.

### Pipeline Blockage

One of the most common reasons for pipeline blockage is that the designer does not select the correct combination of pipeline bore, air mass flow rate and pressure drop required to achieve the desired throughput over the specified distance. The selection of the optimum conveying line inlet air velocity is critical. This is influenced very significantly by the material properties and the mode of conveying. As was mentioned earlier, the ESP ash can naturally be conveyed in dense phase with a low value of inlet air velocity, whereas the economiser ash typically requires a minimum of 13 m/s to achieve successful conveying through the pipeline. The properties of the material are the key factor in the type of system suitable for the given application. An inefficient combustion process can also result in fly ash which has much coarser particles and thus may require a higher conveying velocity.

### Other Fault Situations

The conveying system is generally designed for normal operating conditions of the plant. This would mean that the temperature of the ash to be handled, the removal rate and the grade of the ash would be taken into account to select the operating variables. In practical situations, however, it is not uncommon to expect that the plant can be suddenly shut down for a period, with ash left in the hoppers. In such a situation the ash would cool down. The influence of temperature in such situations must be considered to ensure that the operating velocity range is acceptable.

## POWER STATION ASH HANDLING

It was pointed out above that ash is collected in the economiser hoppers, air pre-heater hoppers and ESP hoppers. There are wide differences in the properties of the ash collected at these various locations. These are in terms of quantity of ash collected in different hoppers, its temperature, particle size distribution, and its behaviour in the gas-solid flow in the pipeline. The design of the pneumatic conveying system should, therefore, consider all of these variables so that the operating conditions can be selected according to the grade of ash being conveyed.

An exhaustive test program was undertaken at the Indian Institute of Technology in New Delhi in 1998/99 to convey different grades of fly ash through a pneumatic conveying pilot plant. A pipeline test loop of 130 m length and 63 mm bore was used to convey the material. Very large differences were observed in the conveying potential of economiser ash and ESP ash. The minimum conveying air velocity at which ESP ash could be conveyed was about 3 m/s, compared with 13 m/s required to convey the economiser ash. This means that the fine ESP ash could be conveyed in dense phase flow while the coarse economiser ash could only be conveyed in dilute phase suspension flow. This reinforces the point that different grades of the same material could have entirely different conveying behaviour in the pipeline, and the designer of the ash handling system should be aware of these differences.

The dry fly ash handling system at thermal power stations consists of two stages. The ash from the economiser hoppers, air pre-heater hoppers and the ESP hoppers is first evacuated to a number of buffer silos. These silos are typically located within a distance of 150 m from the last field hoppers of the electrostatic precipitators. If required, it is possible at this stage to separate the very fine ash, such as that in fields 3, 4 and 5, from the coarser ash in fields 1 and 2. From the buffer silo the ash is generally transported to another silo from where the ash is ultimately cleared from the site. The distance of the disposal silo from the buffer silo could be between 800 m and 2000 m. A typical layout of this arrangement is shown in Figure 5.

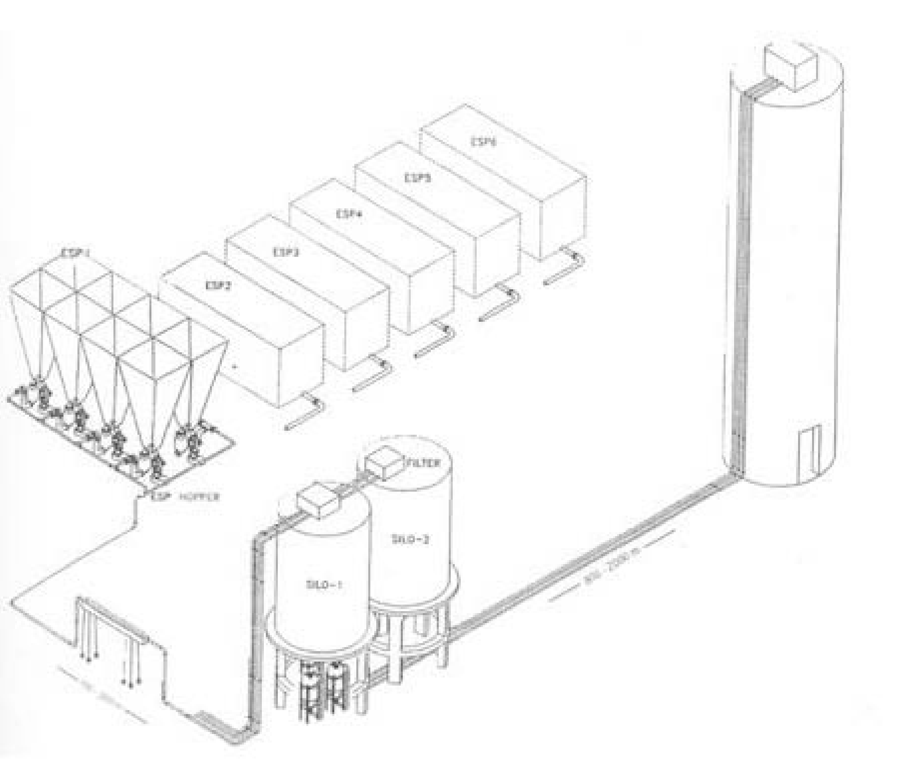



Figure 5: Typical Dry Fly Ash Handling Arrangement at a Power Station

For evacuation of ash from the economiser and air pre-heater hoppers either positive or negative pressure conveying systems can be used. For the second stage of long distance conveying from the buffer silo to the disposal silo, however, only positive pressure conveying systems can be used. It has been experienced that a small percentage of coarse material could be carried along with the fine material. If the quantity of coarse material is significant, however, the operating variables must be so selected that the design caters for the worst conveying conditions. In a power plant, it is desirable to handle the economiser ash separately from the ESP ash.

If the conveying distance from the buffer silo to the disposal silo is more than 1000 m, high conveying air pressures will generally have to be used. Within the practical limits of the pressure drop, the material would be conveyed at a lower value of material to air ratio. In such a situation a higher conveying line inlet air velocity has to be used. The high pressure will result in a higher exit velocity. In such applications it is generally recommended that the pipeline should be stepped to a larger bore part way along its route. This helps to reduce the velocity and improve the performance of the conveying system. Stepped pipelines will be discussed in more detail in subsequent chapters.

# CHAPTER 2

# REVIEW OF SYSTEMS

# CONTENTS

# INTRODUCTION

A wide range of pneumatic conveying systems are available, and they are all generally suitable for the conveying of fly ash, and most other bulk particulate materials. The majority of systems are conventional, continuously operating, open systems, in a fixed location. To suit the material being conveyed, or the process, however, innovatory, batch operating and closed systems are commonly used, as well as mobile systems. To add to the complexity of selection, systems can be either positive or negative pressure in operation, or a combination of the two. In this brief review some of the more common systems are presented, and an explanation is provided of the different types to help in the selection process.

Numerous requirements of the conveying system, and conditions imposed by the material to be conveyed, also have to be taken into account in the selection process. A check list is provided, therefore, of possible system requirements, and specific features of bulk particulate materials, as these may ultimately dictate choice. It must be appreciated that the requirements and capabilities of fine fly ash, coarse fly ash, granular ash, such as from a fluidised bed boiler or crushed bottom ash, and mill rejects, are all likely to be very different.

# SYSTEM TYPES

The problem of system selection is illustrated in Figure 6. This shows the combinations that are possible for conventional pneumatic conveying systems with a single supply of air. Only system types are presented in detail, with positive pressure, vacuum, and combined positive and negative pressure system considered, in relation to both open and closed systems [Ref 4].

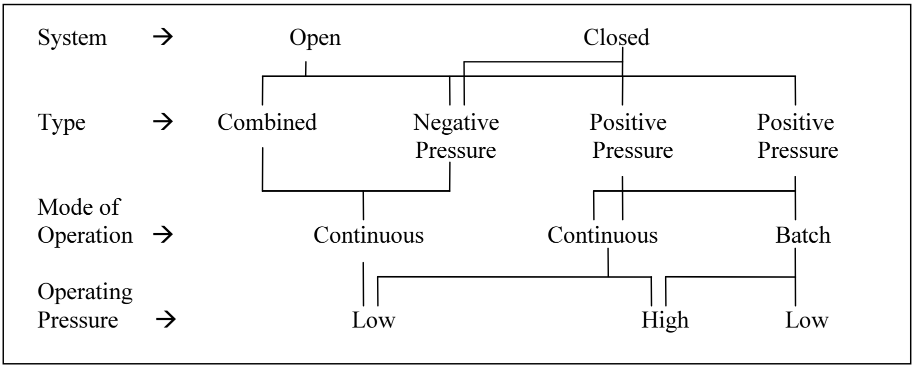



Figure 6: Diagram to Illustrate the Wide Range of Conveying Systems Available For Conventional Systems Operating with a Single Air Source

Material feed into the conveying pipeline is expressed in terms of mode of operation and feeding devices are considered further in a section of these notes that follow. With a natural limit on operating pressure with vacuum systems, air requirements are included here in terms of a high or low operating pressure. Air movers are also considered separately in a following section of these notes.

## Closed Systems

For certain conveying duties it is necessary to convey the material in a controlled environment. If a dust cloud of the material is potentially explosive, nitrogen or some other gas can be used to convey the material. In an open system such environmental control can be very expensive, but in a closed system the gas can be recirculated and so the operating costs, in terms of inert gas, are significantly reduced.

If the material to be handled is toxic or radioactive, it may be possible to use air for conveying, but very strict control would have to be maintained. A closed system would be essential in this case. Continuous conveying systems are probably the easiest to arrange in the form of a closed loop. A sketch of a typical system is given in Figure 7 and is included for reference purposes only. It is most unlikely that a closed system would be required for the pneumatic conveying of any of the grades of ash likely to be encountered, and so it is not considered any further.

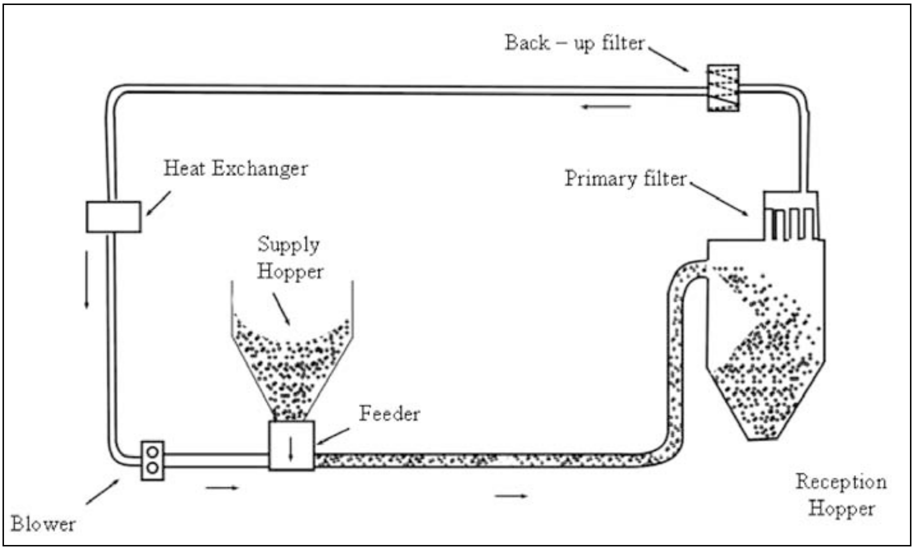



Figure 7: Sketch of Typical Closed Loop Pneumatic Conveying System

## Open Systems

Where strict environmental control is not necessary an open system is generally preferred, since the capital cost of the plant will be less, the operational complexity will be reduced, and a much wider range of systems will be available. Most pneumatic conveying pipeline systems can ensure totally enclosed material conveying, and so with suitable gas-solid separation and venting, the vast majority of materials can be handled quite safely in an open system. Many potentially combustible materials, such as powdered coal and sawdust, are conveyed in open systems by incorporating necessary safety features.

## Positive Pressure Systems

Although positive pressure conveying systems discharging to a reception point at atmospheric pressure are probably the most common of all pneumatic conveying systems, the feeding of a material into a pipeline in which there is air at a high pressure does present a number of problems. A wide range of material feeding devices, however, are available which can be used with this type of system, from verturis and rotary valves to screws and blow tanks, and these are considered in detail later. A sketch of a typical system is given in Figure 8.

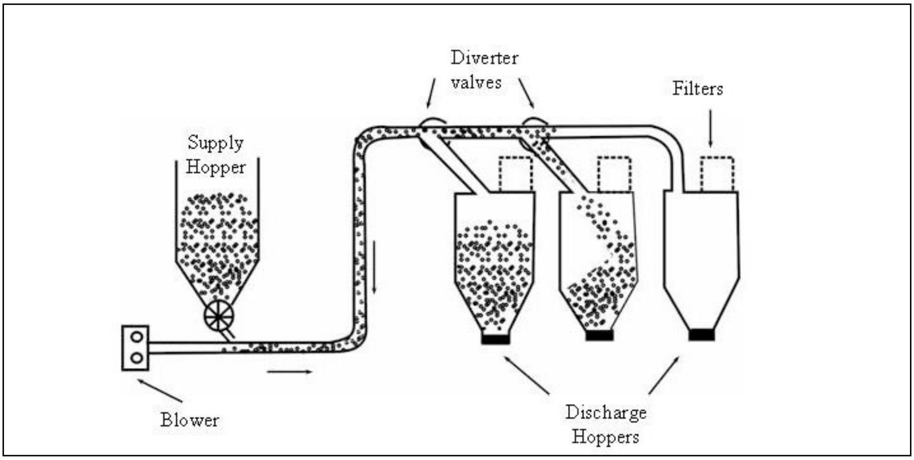



Figure 8: Sketch of Typical Positive Pressure Conveying System

With the use of diverter valves, multiple delivery to a number of reception points can be arranged very easily with positive pressure systems. Although multiple point feeding into a common line can also be arranged, care must be taken, particularly in the case of rotary valve feeding of the pipeline, since air leakage through a number of such valves can be quite significant in relation to the total air requirements for conveying.

## Negative Pressure (Vacuum) Systems

Negative pressure systems are commonly used for drawing materials from multiple sources to a single point. There is little or no pressure difference across the feeding device and so multiple point feeding into a common line presents few problems. As a result the rotary valve and screw can also be a much cheaper item for feeding a pipeline in a negative pressure system than in a positive pressure system. The filtration plant has to be much larger, however, as a higher volume of air has to be filtered under vacuum conditions. A sketch of a typical system is given in Figure 9.

Negative pressure systems are also widely used for drawing materials from open storage and stockpiles, where the top surface of the material is accessible. This is achieved by means of suction nozzles. Vacuum systems, therefore, can be used most effectively for cleaning processes, such as the removal of material spillages and dust accumulations.

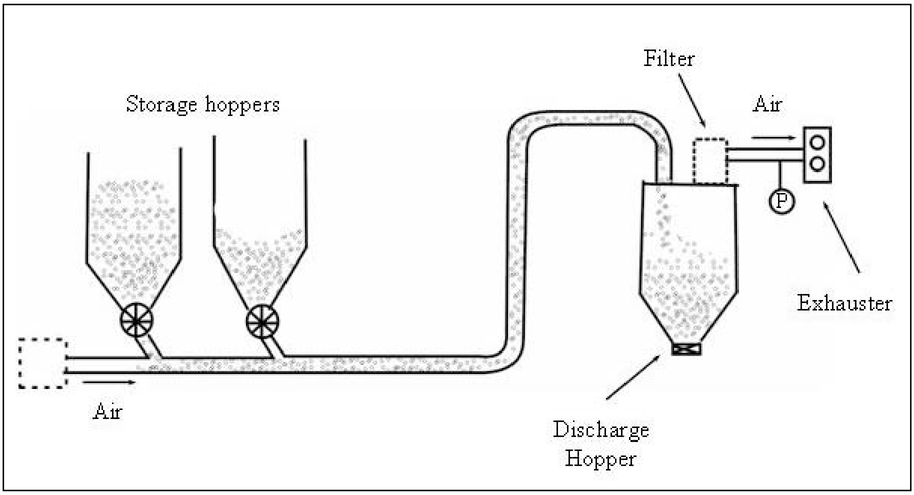



Figure 9: Sketch of Typical Negative Pressure Conveying System

A sketch of a typical negative pressure conveying system operating with a vacuum nozzle is given in Figure 10. This clearly illustrates the potential flexibility of the system. Such conveying systems can be mounted on a truck or lorry and hence have total mobility for the purposes of clearing spillages and accumulations of materials, as mentioned above.

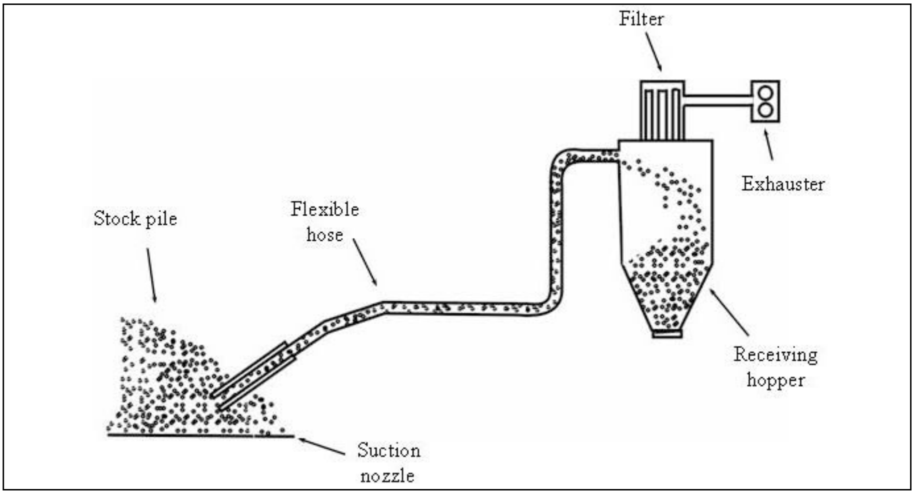



Figure 10: Sketch Illustrating Vacuum Conveying from Open Storage

Vacuum systems have the particular advantage that all gas leakage is inward, so that the injection of dust into the atmosphere is virtually eliminated. This is particularly important for the handling of toxic and explosive materials, or any material where environmental considerations have to be taken into account.

As a result of the conveying air being drawn through the air mover, it is essential that the exhauster should be protected from the possibility of the failure of one or more of the filter elements in the gas-solids separation system. This can be achieved by incorporating a back-up filter, as is shown in Figure 7 for the closed loop system.

## Combined Negative and Positive Pressure Systems

Combined negative and positive pressure systems represent a very versatile type of pneumatic conveying, combining many of the features of the negative pressure and positive pressure systems. They are often referred to as suck-blow or push-pull systems. They can be used to transfer material from multiple sources to multiple discharge locations and can thereby extend vacuum systems over much longer distances. Protection has to be provided for the exhauster/blower from the possible ingress of material, as with negative pressure systems.

It should be noted that the available power for the system has to be shared between the two sections, and that the pipelines for the two parts have to be carefully sized to take account of different operating pressures, and possible air leakage across the feeder for the positive pressure part of the conveying system. Some air movers, such as Roots type blowers, operate on a given pressure ratio, and this will mean that the machine will not be capable of operating over the same pressure range with the combined duty as compared with their individual operation. A sketch of a typical system is given in Figure 11.

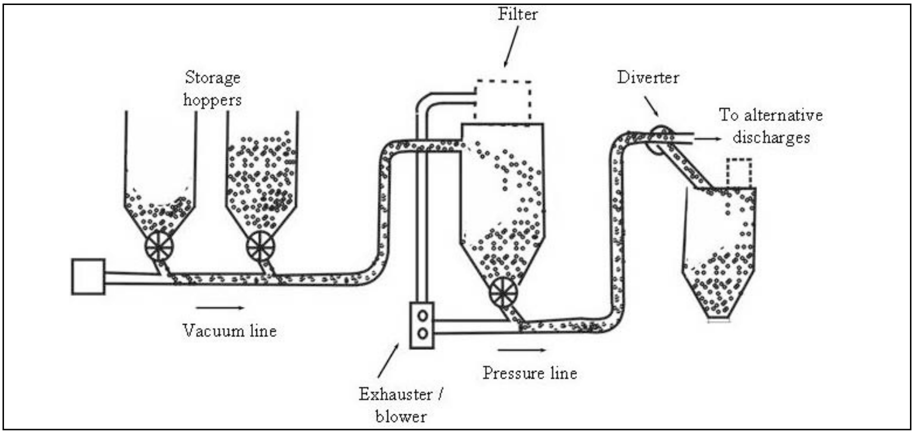



Figure 11: Sketch of a Combined Negative and Positive Pressure System

## Dual Vacuum and Positive Pressure Systems

If the conveying potential of a system requiring the vacuum pick-up of a material needs to be improved beyond that capable with a combined negative and positive pressure system, particularly in terms of conveying distance, then a dual system should be considered. In this combination the two conveying elements are separated and two air movers are provided. By this means the most suitable air mover can be dedicated to the vacuum system and the most appropriate positive pressure system can be used for the onward transfer of material.