

2 REVIEW OF THE LITERATURE

2.1 INTRODUCTION

A number of completely different disciplines have been studied and used in this research work to disseminate information about the erosion resistance of tungsten carbide in pneumatic conveying systems vis a vis:

- * The science of pneumatic conveying
- * The erosion of pneumatic conveying pipelines and erosion in general
- * Mechanical properties of tungsten carbide
- * The erosion of tungsten carbide

Each discipline has been discussed separately to facilitate the understanding of their interrelationship and hence of the results of the research as a whole.

2.2. PNEUMATIC CONVEYING

2.2.1 INTRODUCTION

Pneumatic conveying is the transportation of a wide variety of dry powdered and granular solids in a gas stream, normally air. It has become a popular method of materials handling over the past few years. This is so because pneumatic piping can easily be routed along walls and ceilings to avoid obstructions, without radical structural modifications, and hence large savings in floor space are possible.

2.2.2 BASIC THEORY OF PNEUMATIC CONVEYING

Pneumatic conveying systems can be divided into the following four distinct zones (1) and each zone has its own specialized hardware:

- a) The prime mover
- b) Feeding, mixing and acceleration
- c) Conveying
- d) Gas/solid separation

a) The prime mover

The prime mover is a compressor, blower, fan or vacuum pump, either one of which is used to provide the necessary energy to the conveying gas. The choice of which type of prime mover to use is dependant on the gas flow rate and conveying pressure required to effect reliable transportation.

b) Feeding, mixing and acceleration zone

This zone is considered one of the most crucial areas in any pneumatic conveying system. In this particular zone the solids are introduced into the flowing gas stream by way of some kind of feeding system. The more common feeding systems are rotary valves, vibratory or venturi feeders. By virtue of the fact that the solids are initially at rest, a large change in momentum occurs when the solids are introduced into the flowing gas stream. Associated with this momentum change, is the need to provide an acceleration zone.

If the physical space permits, the zone normally consists of a horizontal section of pipe of a precalculated length to allow the solids to reach a "steady state" of flow.

c) Conveying zone

Once the solids have passed through the acceleration zone, they enter the conveying zone. This consists of piping of a suitable diameter. The selection of piping is based on a number of factors including the abrasiveness of the product, pressure requirements, etc.

The conveying zone can have a number of bends and diverter valves in order to change the flow direction. Because a bend constitutes a change of direction, the solids are decelerated as they move through it. At the exit of each bend there is thus a local acceleration zone which tends to re-entrain the solids.

d) Gas/solids separation zone

In this zone the solids are separated from the gas stream in which they have been conveyed. It is only necessary to maintain a pressure drop across the collector which will be sufficient to separate the solids from the gas.

This process takes place at the final or any intermediate distribution point.

The selection of an adequate gas/solid separation system is dependent upon a number of factors, the primary factor being the size of the solids requiring to be separated from the gas stream. Various devices such as bag filters, reverse jet filters and cyclones can be used to effect the separation process.

2.2.3 MODES OF PNEUMATIC CONVEYING

Pneumatic conveying systems can be classified into two distinct categories (1), based on the average particle concentration in the pipeline i.e:

Dilute phase systems

Dense phase systems

Dilute Phase

Dilute phase systems in general employ large volumes of gas at high velocities. The gas stream carries the materials as discrete particles by means of lift and drag forces acting on the individual particles. Dilute phase systems constitute the most widely used of all pneumatic conveying systems.

Dense Phase

A reduction in the gas velocity to a lower value than the saltation velocity (velocity at which the particles become stationary) results in a non-uniform distribution of solids over the cross section of the conveying pipe.

The conveying process takes place with a certain proportion of the solids flowing through the upper portion of the cross-section of the pipe, together with a highly concentrated solid stream progressing at a lower velocity in the lower part of the cross-section. The flow patterns can vary from being unstable to stable or an intermediate unstable/stable regime.

Flow patterns in the dense phase mode can vary from conditions in which the solids completely pack the pipe and move as a continuous dense plug, to situations where the solids on the bottom of the pipe move as a series of dunes with a dilute phase layer of solids flowing above the dunes.

State diagram

The gas/solids conveying process is best described by means of the "state diagram" (1).

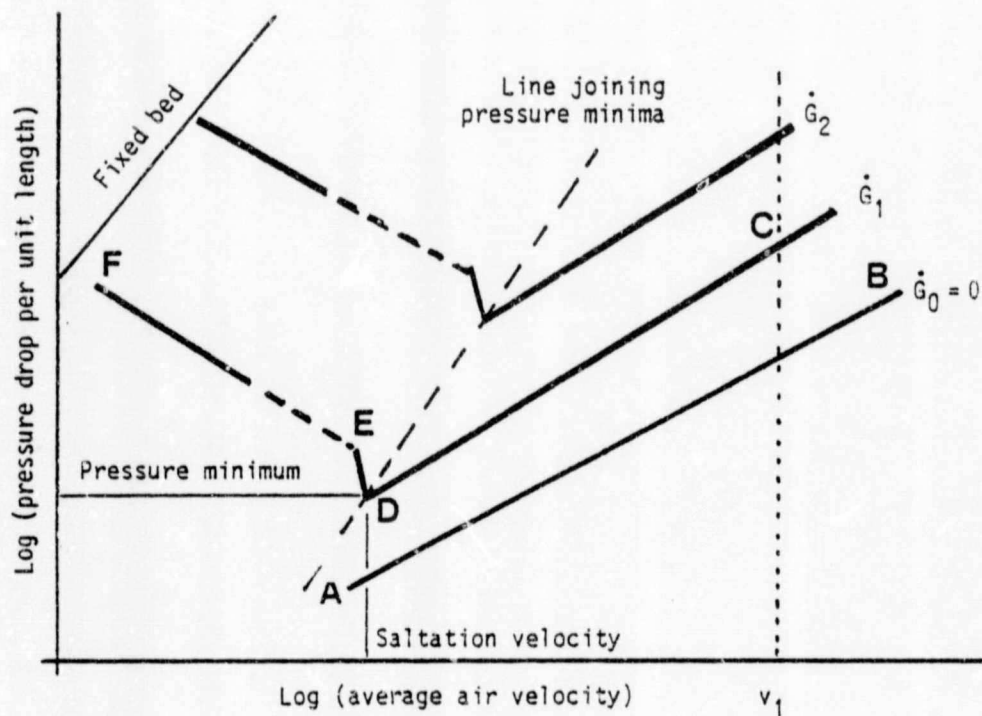


Figure 1. State diagram for horizontal conveying. (After Marcus, Chambers and Ratcliff, 1)

The state diagram has been drawn for a horizontal flow system and is a plot of the pressure gradient per unit length of pipe ($\Delta P/L$) at any point in the pipeline, versus the gas velocity. The whole spectrum from dilute phase to dense phase is illustrated by means of this diagram.

Line AB represents the friction loss for a horizontal pipeline transporting gas only. At an air velocity (V_1), homogeneously sized particles are introduced into the pipeline at a constant feedrate $\dot{G}_0$. As a result of drag on the solid particles and also due to particle-wall interaction, the pressure drop increases from B to C.

Decreasing the air velocity along the path CD, the particle velocity is reduced and the mass flow ratio is increased, resulting in a smaller solids frictional loss.

Point D represents the condition at which all solids can just be transported as a suspension in the dilute phase with the prevailing air velocity and imposed solids feedrate $\dot{G}_1$. At this juncture the system would just operate in a steady flow state. The critical air velocity corresponding to point D is called the saltation velocity.

At point D, the saltation point, a slight decrease in gas velocity will result in a substantial deposition of solids (bed formation). This results in a sharp jump in the frictional resistance to point E. With a further decrease in gas velocity (EF), the solids flow will be partly carried out in the suspension above the solid layer and also by way of slug flow in the stationary bed itself. Once again, by virtue of the higher solids loading an increase in pressure is noted.

Superimposed on the state diagram are curves showing the situation for higher solids mass flow rates ($\dot{G}_2$). Note that the characteristic curve for each solid mass flow rate passes through a pressure minimum at the saltation velocity.

Of importance is the curve obtained by connecting the pressure minimum for each solids flow rate condition. In particular, it can be seen that the curve moves upwards to the right thereby indicating that at higher solids loading, the saltation velocity increases. This particular aspect is of vital importance to system designers. It shows that, should a system be designed to transport solids at a particular solids feedrate, (and it is desired to increase the solids feedrate), it is necessary to increase the conveying velocity and hence gas flow rate to ensure stable operation.

Optimum operating conditions for dilute phase systems are generally just to the right of the line joining the pressure minima.

Wear in Pneumatic Conveying Pipelines

The use of freight pipelines has led to an increasing demand for systems to be developed which can transport larger and more abrasive products. In parallel with such developments is the need to obtain a better understanding of the wear mechanisms which take place during fluid/solid transportation processes. The following section deals with the current understanding of the erosion of pipe bends.

2.3 REVIEW OF EROSION OF PIPE BENDS

2.3.1 Introduction

The erosion of materials by the impact of solid particles is a wear process in which material is removed from a surface by the impingement of small hard particles, usually accelerated by a gas flow (9). The phenomenon of erosion has received much attention during the past 20 years. It has been recognised as an important wear mechanism in chemical plants, coal combustion machinery and oil refineries. In all these areas of mechanical and chemical engineering, erosion has shown itself to be an economically important degradation process.

Pneumatic conveying, having become a viable means of materials handling, has brought with it its own erosion problems. This section deals with the parameters affecting the erosion of pipe bends in particular. Where applicable, the erosion phenomena associated with pipe bends has been compared to erosion in general.

2.3.2 THEORY OF EROSION

The following definition is generally used to describe erosion (7):

$$\text{EROSION} = \frac{\text{MASS WORN FROM SURFACE}}{\text{TOTAL MASS OF IMPINGING PARTICLES}}$$

There are obviously a number of factors that influence erosion, but this relationship simplifies the erosion process, and is described by curve (a) of figure 2, Pg 15.

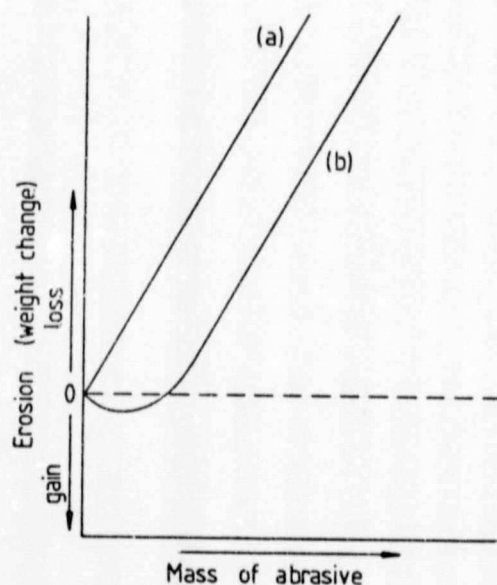


Figure 2. Change in specimen weight as erosion takes place.
(After Hutchings, 7).

For some materials, grit particles may become embedded in the surface and cause an initial weight gain, as shown by curve (b). After this incubation period, which is observed mainly with soft target materials at normal incidence, the erosion progresses linearly with the mass of impacted grit particles. For most target materials, the incubation period is negligible and the weight lost from the surface is closely proportional to the total mass of grit particles which have struck the surface, hence line (a) is followed. It appears that the mechanisms of material removal (ductile or brittle) are dependant on the type of material being eroded. Considering that this research work is concerned with the erosion of tungsten carbide, a complex dual phase material that exhibits both ductile and brittle modes of fracture, a brief discussion of the mechanisms of material removal follows.

2.3.3 Mechanisms of erosion

Ductile erosion

When a particle strikes a metal surface, the nature of the deformation depends on the properties of the particle and of the metal, as well as the velocity and geometry of impact.

Studies of the impact of single particles on ductile metal surfaces (7) have shown several ways in which material is removed.

Figure 3, Pg 17, shows the three major types of surface damage that can result from the oblique impact of irregular particles on to a ductile metal surface. Three types of metal removal can be distinguished:

Ploughing

Type 1 cutting

Type 2 cutting

Ploughing damage (figure 3(a)) results when the particle strikes with a rounded part of its surface. Metal is pushed up above the crater to form a lip at the exit end of the crater. This lip may become detached if the impact velocity is high enough, or be vulnerable to removal by a subsequent impact.

Type 1 cutting occurs when a corner of the impacting particle indents the surface and the particle rolls forwards on the surface, raising material into a prominent and therefore vulnerable lip. (Figure 3(b)).

Type 2 cutting is observed for a narrow range of impact angles and particle geometries. This type of cutting resembles a machining action whereby the sharp corner of an abrasive grain cuts a chip from the surface while rotating backwards, resulting in the damage shown in figure 3(c).

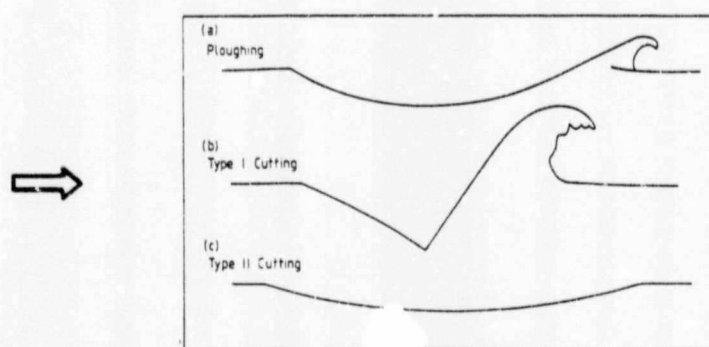


Figure 3. Three types of impact damage which can be distinguished for hard particles striking a plane metal surface. The impact direction is from left to right. (After Hutchings, 7)

While clear distinction can be made between these three types of deformation when single particles strike a surface, the erosive mechanisms are more complex when randomly oriented irregular particles impinge on a previously eroded and hence very irregular surface.

Thus theoretical models that have been proposed to predict wear are based on single particle impactions and are extrapolated to describe the erosive behaviour of the more practical multiple particle impact. Nevertheless, examination of eroded surfaces and of erosion debris by electron microscopy confirms that extensive plastic flow of the surface is associated with the erosion of metals, and that the most important mechanism of metal removal is the detachment of fragments of metal comparable in size and shape with the lips raised by plastic flow around individual impact

sites. It has also been proposed that heating of the material has an influential effect on the erosion process (8).

Brittle erosion

Microscopic examination reveals that in materials which exhibit the characteristic variation of erosion with impact angle, the principal erosion mechanism is one of brittle fracture, accompanied by only a small amount of plastic flow. As in the case of the completely plastic deformation processes, models for the erosion of brittle materials have been based on the damage caused by single particle impacts on a plane surface. Although the mechanism of material removal is brittle fracture, some degree of plastic flow usually occurs immediately beneath the impacting particle.

Dual phase erosion

Dual phase erosion is a complex combination of ductile and brittle erosion. In general, dual phase materials are eroded by the preferential removal of the soft binder or matrix material, followed by the fracture and/or extracture of the hard particles. (See section 2.5.5, Modes of material removal, Pg 49).

Keeping the above theories in mind, but considering now the erosion of pipe bends in particular, there are a number of pneumatic conveying parameters that influence this erosion, and these will be discussed forthwith.

2.3.4 CONVEYING PARAMETERS

Air velocity

The velocity of the conveying gas is probably the single most important variable in erosive wear problems. Power law relationships for specific erosion rates (mass eroded per unit mass of product conveyed) have now been well established (6,7,8,10), albeit using bench top type erosion rigs in which particles are blasted against flat test surfaces at various impact angles. Recent work by Mills and Mason (9) on actual pipe bends has shown that the results correlate very well. They obtained the following relationship for 140 mm radius, 50 mm bore mild steel bends:

$$\text{specific erosion} = K * \text{conveying air velocity}^{2.65}$$

where K is a constant. This means that the erosion at a velocity of 30 m/s will be approximately double that at 23m/s and treble that at 20 m/s.

These authors have also shown that the depth of penetration of the particles into the bend wall surface, for a given mass eroded, increases with an increase in velocity, and have proposed a modified power law relationship of:

$$\text{pipe bend erosion} = K * \text{velocity}^{4.5}$$

This means that bends will fail in an even shorter time than that predicted by specific erosion results alone.

Effect of secondary flows

It has been found that the erosion results at low conveying velocities are erratic compared to high conveying velocities. Mills and Mason (9) have confirmed previous suggestions that erosion results may be influenced by a threshold velocity below which no erosion takes place, and that this threshold value is a function of particle size, being very much higher for rounded rather than for angular particles.

It is therefore the opinion of these authors that the erratic results and hence premature bend failures are as a direct result of secondary flows of the suspensions in the bends, as particles in suspension (especially fine particles) are likely to be influenced by such secondary flows at low velocities.

Effect of condition of the conveying product on velocity

Figure 4, Pg 21, is a log plot showing the variation of specific erosion with velocity for 230 micron sand conveyed at a phase density of 2.0.

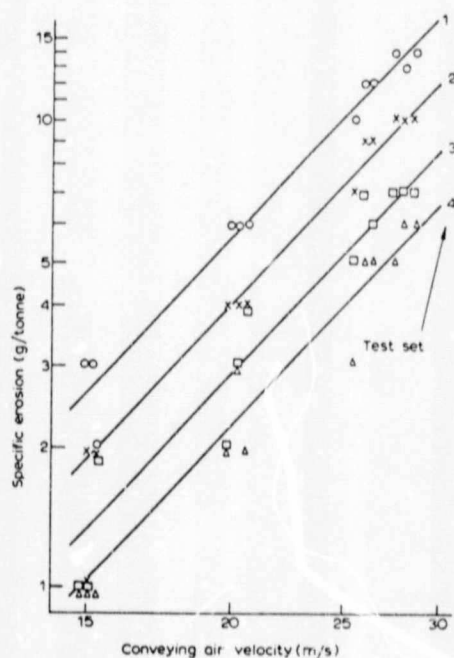


Figure 4. Variation of specific erosion with velocity.
(After Mills and Mason, 2)

The results plotted are cumulative values and the gradual reduction in specific erosion (seen by test sets 1 to 4 in figure 4) can be attributed to progressive degradation and wear of the conveyed product.

Phase Density

From work on the erosion of flat plates in sand blast type test rigs, it has generally been concluded that the effect of particle concentration or phase density (ratio of solids/air mass flow rates in the pipe), is minimal.

Dolganov and Shteinberg (11) concluded that in the pneumatic transport of crushed iron-vanadium concentrates in a 50 mm diameter pipe, the specific erosion does not depend on the concentration of material in the gas stream, but that the absolute erosion is proportional to the quantity of material transported.

Mills and Mason (12), however, have established that for pipe bends this is not the case. They have shown that not only can the phase density affect mass eroded from the surface quite considerably (depending on the state of particle degradation), but that an increase in phase density can have a marked influence on decreasing the mass eroded from a bend to cause failure i.e. the depth of penetration becomes the determining factor.

Figure 5, Pg 23, is a plot of penetration rate in microns per gram eroded against phase density.

Over this phase density range, therefore, bends through which powders are conveyed at high phase density will fail after much less product has been conveyed, compared with bends through which powders are conveyed at low phase density.

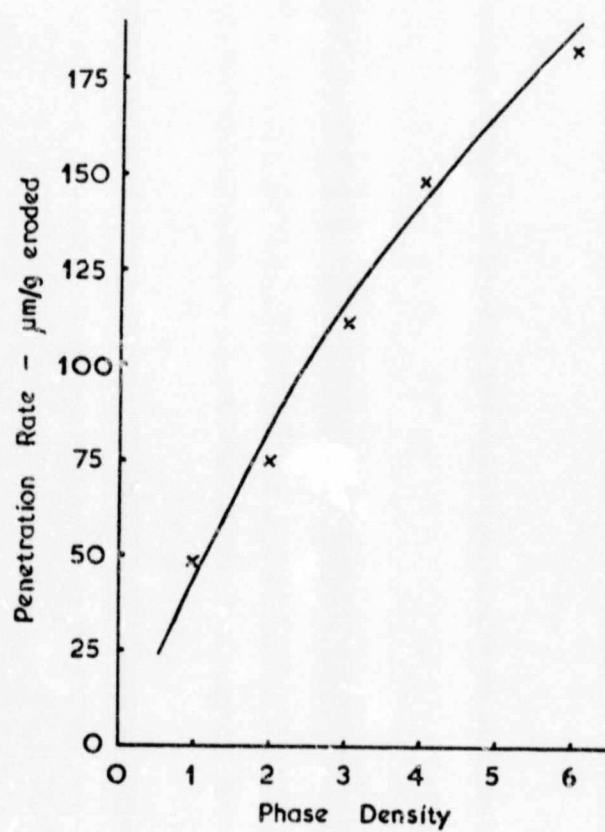


Figure 5. Variation of penetration rate with phase density.
(after Mills and Mason, 14)

Mills and Mason (12) have shown that the phase density also affects the appearance of the eroded surface, and that the higher the phase density, the greater the scatter involved in the test results.

It is thought that a change in phase density will give rise to an increase in the interference of the impacting particles between each other as well as between the particles and the eroding surface. This interference causes shielding of the eroding surface to occur and hence less erosion takes place. Figure 6, Pg 25, shows the log-log results of tests carried out using 140mm radius, 50mm bore mild steel bends using worn and degraded 70 micron sand. The slope of the line is $-.37$, which means that the erosion can be expressed by

$$\text{erosion} = \text{constant} * (\text{phase density})^{-.37}$$

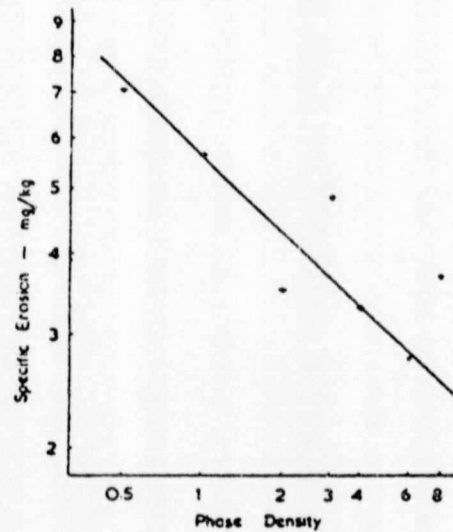


Figure 6. Variation of erosion with phase density for 70 micron sand. (After Mills and Mason, 12)

Effect of condition of conveyed product on phase density

Figure 7, Pg 26, is a log plot of the erosion results using 230 micron sand. The four lines correspond to the test results for the four sets of tests carried out. The results plotted are cumulative values, and the gradual reduction in specific erosion can be attributed to the progressive degradation and wear of the conveyed product.

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