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Effect of Bend Geometry on Erosion and Product Degradation in Pneumatic Conveying Pipeline Systems

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ABSTRACT

Conveying hard and the abrasive materials has been one of the major operational problems in industrial situations. The erosion of plant components, especially the pipe bends by abrasive solid particles of a fluid stream makes installation of pneumatic conveying systems a very costly affair for industry. Most users have either lived with the problem or have employed expensive bend materials to reduce the bend erosion rate and prolong the life of bends. A number of operating variables such as the impact velocity and impact angle affect the erosion and product degradation process significantly in a dilute phase suspension flow. It is therefore important that the systems should be designed with the lowest possible velocity of conveying. Modification in the pipeline - bend geometry by means of tapered (converging and diverging) sections can also be used for maintaining conveying air velocity constant along the entire length of pipeline.The current work presents erosion of G.I. bends examined in a pneumatic conveyor under two different arrangements of mild steel pipe and G.I. bends of 51mm and 102mm bore in a test loop of 40 m length. Silica sand particles having mean particle size of 212 µm were used as erodent for impingement on the bend surface. This paper discuss the results of comprehensive test program to study the effect of bend geometry on erosion and product degradation in pneumatic conveying pipeline systems .

(**Key words:**Bend Erosion, Dilute Phase Suspension, Pneumatic Conveying Systems, Product Degradation, Silica Sand)

1.INTRODUCTION

Material handling, in the industries, is concerned with movement of materials in different cases such as from supply point to store or process, between stages during processes, or to packing and distribution. The transportation of wide variety of dry powdered and granular solids in a gas stream through pipelines is generally termed as pneumatic conveying. In most cases the gas is normally air. However, where special conditions prevail (e.g. risk of explosion, health, fire-hazards etc.), different gases are used. It provides an important method of transporting the bulk materials. It is successfully used for transporting wide range of materials. The concept of pipeline transportation of fluids is by no means modern. The history of its use dates back to antiquity. The Romans, for instance used lead pipes for water supply and sewerage disposal, whilst the Chinese conveyed natural gas through bamboo tubes. The record of pipeline transportation of solids in air is more recent with the inception of fans to activate the first pneumatic conveying in 1866.The first large scale application of pneumatic conveying was the vacuum conveying of grain in the late 19th century. By the mid 1920's,negative and positive pressure conveying of grain was common. Since that time the practice of pneumatic conveying has grown enormously and has extended to cover a wide variety of particulate solids like silica sand; alumina, cement, sugar, flour, plastic granules etc.[1].Pneumatic conveying system is particularly suitable for handling toxic and hazardous materials and is extensively used in chemical process industry,pharmaceutical industry, mining industry, agricultural industry, mineral industry, and food processing industry. Virtually, all powders and granular materials can be transported using this method [2].

Researches during the last two decades have helped the designers to design the reliable and energy efficient pneumatic conveying systems. This design method of handling a wide range of bulk solids is still in a developing stage primarily due to the complex nature and interdependence of the operating variables and the variety of materials that can be conveyed. The nature of such a material principally depends on the size, shape and density of the constituent particles. Preliminary Investigations into the phenomenon of erosion in pneumatic conveying bends reported to 1970's showed that the most significant variables with respect to erosion damage were conveying velocity, particle concentration, particle size, particle shape and bend geometry [3]. Erosion and other problems has been tried to be associated with successful design of pneumatic conveying systems showing that the erosive wear behaviour of rubber and mild steel is very much product dependent[4]. Since then, the importance of penetration rate in predicting the failure of pneumatic conveying bends has been realised and has been the subject of numerous research activities.

2. PNEUMATIC CONVEYING SYSTEM

Pneumatic conveying system is a conventional material handling system like belt conveyor or chain conveyor.The main advantage of pneumatic conveying system is that material is transferred in close loop, thereby preventing the environmental
effect on the material and vice versa. Other benefits of the system includes

- flexibility of routing and installation of pipeline
- reduced maintenance and labour cost involved
- relatively low capital costs and increased automation
- multiple pick up and discharge points
- product safety.

The main disadvantages with the system are the erosion of components like bends ,diverters , pipelines and the quality degradation of conveyed product [5].

A typical pneumatic conveying system comprises of four basic units, viz; air mover ,feeder,conveying pipe line loop and filteration unit.Air mover supplies the specified volumetric flow rate of the free air maintaining the appropriate pressure in the conveying system. Air movers available for the pneumatic conveying system applications ranges from the fans and blowers producing high volumetric flow rates at relatively low flow rates and vice versa.Feeder is a device that is intended to feed the material in to the conveying loop uniformly and that to with lowest leakages. Numerous devices have been developed to feed the materials in to the pipelines; some of them are blow tank, rotary valve, screw feeder etc.Blow tank is a type of feeder, which could serve the purpose both for low and high-pressure requirements. Material and air mixture is conveyed through the pipeline loop, containing some stipulated number of bends to provide flexibility of routing. The material of the pipeline is usually mild steel. The bends can, however be made of a hard, erosion resistant material. Bends can be used as horizontal section or as a vertical section in the loop depending upon the flexibility of installation.Filteration unit is a gas solid separation device performs two functions. Firstly, it recovers conveyed material as much as possible for the next stage of handling or treatment process. Secondly, it minimizes the pollution of the working environment.

Based on the quantity of air used and pressure of the system, pneumatic conveying system is divided in to two types ie. dense phase pneumatic conveying system and dilutes phase pneumatic conveying system. In dilute phase conveying, solid particles are introduced into a fast flowing gas stream where solids remain suspended. Such process systems operate at relatively low pressure and consequently are comparatively inexpensive to install.Dense phase pneumatic conveying is defined as the conveying of particles by air along a pipe which is filled with particles at one or more cross-sections. A wide range of different pneumatic conveying systems are available to cater for an equally wide range of different applications. Pneumatic conveying systems can be positive pressure systems that blow material along a pipeline or negative pressure systems that convey material by means of suction. In general positive pressure systems are extremely versatile due to large pressure drop available and can convey material with a capability to handle both high product throughputs over short distances and low product throughputs over long distances [6].

3. VARIABLES ASSOCIATED

The factors involved in many of the problems associated with the pneumatic conveying systems can be grouped in to the following categories:

- The variables associated with the conveyed product.
- The variables associated with the carrier medium.
- The variables associated with the pipe surface material.
- The variables associated with the geometry of system.

The first two factors covers the particles being transported and carrier gas employed, the third one covers the pipe surface material and the fourth one covers the geometry of the system. Pipeline bends suffer from major losses due to erosion. Severity of erosion at the bends and diverters etc. is more because there is change of direction of gas solids suspension flows at these components. The main factors affecting bend erosion and consequently affecting the conveyed product quality are particle velocity,size,shape and bend geometry [7].

Amongst all the variables that influence the problem of erosion for a particular product and the bend material, velocity is probably the most important of all. From extensive studies on erosion,it is now generally accepted that the increase in the mass eroded from a surface with increase in the velocity can be represented by a power law relationship;where the velocity exponent (n) is of order of about 2.5 [8].

$M = C \times V^n \longrightarrow 1$, where

M_e = mass eroded from the bend in grams.

V_p = velocity of impacting particles in m/s.

C = a constant.

With velocity being the most important operating variable influencing the erosion rate, it is therefore important that the systems should be designed with the lowest possible conveying velocity. High conveying air velocities also increase the chances of product degradation; if friable material is conveyed.

The value of particle hardness of the product being conveyed is probably the major indicator of the potential erosiveness of the product. Experimental investigations carried out in 1969 have investigated that erosion is related to hardness by expression :

$M = C \times (H_P)^{2.4} \longrightarrow 2$,where

M_e = mass eroded from the bend in grams.

H_P = particle hardness in kg/mm^2.
C = a constant.

It is generally considered, however, that there is a threshold value of particle hardness, beyond which erosion is decreased or remains relatively constant [9-12]. This occurs at a particle hardness of about 800 kg/mm^2 and so materials with particle hardnesses much greater than this would not be substantially more erosive than the sand particles.

Particle size is another variable that shows a threshold value above which there is no further increase in erosion. Experimental investigations carried out by Tilly have indicated that the threshold value occurs at a particle size of about 60 microns, in the velocity range appropriate to the pneumatic conveying [13,14]. Thus it can be concluded that the threshold value increases with the increase in velocity.

Bend provides pneumatic conveying systems with their flexibility in routing ,but conveying abrasive product in dilute suspension form at higher velocities can lead to rapid wear.Suitable design considerations at the pipeline bend interface can potentially reduce the complications of wear and prove to be economical.Bend geometry refers to the curvature of bends where the particle makes an impact with the surface and the adjoining particles. In order to investigate the potential influence of expanded bends on parameters such as bend erosion, minimum conveying velocity, pressure drop, a series of tests were conducted with two inch bore pipe line conveying silica sand. In the second set of experiments, the last two bends of the pipeline loop were replaced by the two and half inch bore bends.The tests results have shown that the expanded bends presents a potential solution to reduce the severity of erosion. The potential life of the bends has increased to at least four times only by changing a two-inch bore to two and half inch bore bend. The larger bore bend also showed improvements in the product degradation and pressure drop in conveying.

Similarly, experimental study of bend erosion in pneumatic conveying pilot plant with modified test pipeline, have been carried on 53 mm bore and 81mm bore bends; respectively. It has been shown that the bend erosion and product degradation in modified pipeline seems much less comparatively
[15-18]. To a certain extent bend wear is a problem with which industry has learned to live. There are a number of ways by which the severity of the problem can be reduced, but a number of factors relating to the product conveyed and the system itself have to have taken in to account. Expense is obvious a consideration with some methods of solution, some techniques may lead to a reduction in the product conveying capacity of the plant, and if the product being conveyed is friable then a solution which minimizes the effect of degradation must be sought. Favourable operating conditions like conveying air velocity and particle impact angle can be utilised to solve the potential problem of erosion and product degradation. Air is compressible by nature. In a single bore pipeline as the air moves along the pipeline length, some pressure drop takes place. This pressure drop results in excessive high conveying air velocities towards the end of pipeline. So it is needed to be controlled precisely. Tapered sections could be fitted on the upstream and down stream of each bend in the pipeline to cater for the air expansion effect. A tapered section provides modified bend geometry resulting in safer impingement impact angles and lower impact velocities.

4. MECHANISM OF EROSION

Extensive analysis of the eroded surfaces metallographically both of brittle and ductile materials have been carried out by using scanning electron microscope. Based on such analysis various researchers have concluded that the mechanism of erosion can be classified as plastic deformation and cutting wear. Ductile materials; annealed low carbon steel, copper, aluminium etc. erodes predominantly by plastic deformation at low impingement angles (10^0-20^0). Brittle materials; glass, ceramics, cast iron etc. erodes predominantly by cutting or shearing action and shows drastic erosion at higher impingement angles (80^0-90^0).

When an elastically deformable particle impinges on the flat surface, highly localised hertzian stresses are induced due to elastic deformation of both the surface and particles. The maximum induced stress in the flat surface generally occurs at a depth about half the radius of projection of contact area. As soon as the stress induced due to collision between the two goes above the elastic limit of material surface, plastic deformation sets in at the location of maximum stress. This repeated collision of large number of particles forms plastically deformed layers. The plastically deformed layers gets detached from the material surface due to the further collisions. This type of wear is termed as deformation wear. If conveyed hard particles strikes the flat surface at an acute angle and penetrates in to the surface, shear stress is induced in the material over the contact area. Furthermore; if the induced shear stress exceeds the proof shear stress value, material removal from the surface starts. This removal of material by cutting action is termed as cutting wear[19-21].Analysis by various researchers have also shown that there usually exists an incubation period during which little erosion occurs. This incubation period is followed by an accelerated period and then a steady state period.

5. EXPERIMENTATION

5.1Test Rig The pneumatic conveying test rig reported in the work consist of top discharge type blow tank 1m^3 capacity with a safe working pressure of 7-bar gauge used as a product-feeding device for the pipeline. The blow tank is fitted with a fluidising membrane consisting of filter cloth sandwiched between perforated metal plates. The discharge pipe

is positioned about 40 mm above the center of the fluidising membrane. The product is conveyed from the blow tank through the conveying line and is received in to a storage hopper mounted above the blow tank. The storage hopper of capacity similar to that of the blow tank and is mounted on 3 load cells, positioned 120^0 apart in order to record the product mass flow rates. A bag filtration unit with a mechanical shaker is mounted on the top of the hopper to separate air from the product and to retain as much of the conveyed product as possible. Compressed air required for conveying the material is supplied from a two-stage sliding blade rotary compressor. Compressed air from the compressor via. receiver is then passed through a set of two desiccant type air driers connected in series to get dry air free from the moisture. The compressed air line is connected to a nozzle bank consisting of two manifolds, bottom of the blow tank to provide fluidising air to fluidise the product, each containing 8 choked flow convergent-divergent nozzles. The first line is connected to the bottom of the blow tank to provide fluidising air to fluidise the product ,pressurise the blow tank and to discharge the product in to the conveying line. The second line is connected to the discharge line to provide air to convey the product through the pipeline. Both air supply lines are fitted with the isolating valves, pressure gauges and airflow nozzles. The plant test rig is instrumented with nozzle bank containing calibrated nozzles, digital pressure gauges, bourdon type pressure gauges
, multimeter and load cell for the measurement of all the major operating variables (air mass flow rate, product mass flow rate and conveying air pressure) involved in pneumatic conveying systems.

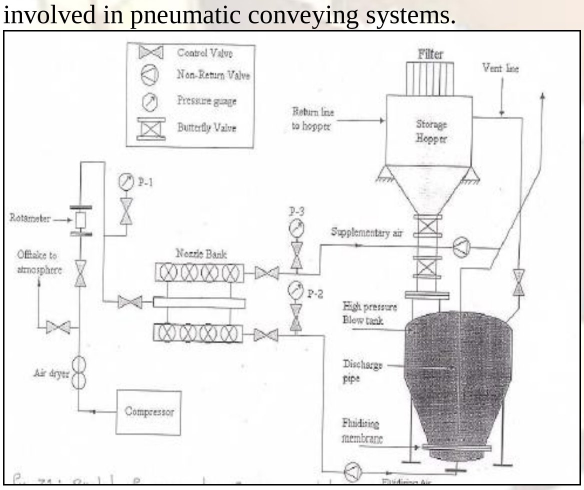

Fig.1. Schematic Diagram of Pneumatic Conveying Test Rig

5.2 Operation and Control After loading thoroughly dried silica sand in to the hopper, the ratio of air supply to the blow tank to that of the total air supply is set to attain the material conveying at a particular velocity. Abrasive is then fed in the blow tank by opening both the butterfly valves. The vent line is kept open for the displaced air from the from the blow tank to escape. There is no valve in the conveying rig at the outlet from the blow tank prior to the conveying line. At the start of each run, conveying commences when the blow tank vent line to the receiver is closed. The blow tank pressure soon builts up to a steady operating pressure to convey the abrasive. The load cell reading and the conveying line pressure drop are to be recorded for each conveying run.

5.3 Conveying Conditions for Constant Bore and Modified Test Pipeline Loop In first phase of the comprehensive test, experiments were performed on 51mm bore pipeline loop fitted with 51mm (constant) bore bends. The bend material was galvanized iron whereas pipeline material was mild steel. The length of pipeline loop was 40 m.

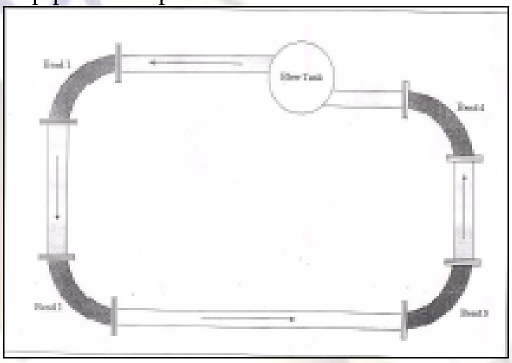

Fig.2. Schematic Diagram of Constant Bore Test Loop

In the second phase, experiments were performed on 51mm bore pipeline loop fitted with 102mm (modified) bore bends. Modification in the bend geometry has been achieved by using tapered sections having larger bore and fitted to the smaller bore pipeline of gradually expanding sections.

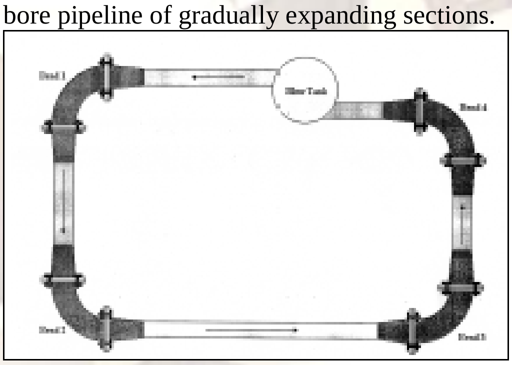

Fig.3. Schematic Diagram of Modified Test Pipeline Loop

tapered divergent section is fitted to upstream of each bend and convergent tapered section is fitted to downstream of each bend. The conveying conditions used for the phase-1 and 2 of test programme are shown in **table 1.** Pipeline loop used in phase-1 and 2 of the programme are shown in **fig.2** and **fig.3.**

Table.1. Conveying Conditions for Test Loops.

Loop/ Test No.	Air flow rate,Kg/s	Product Flow rate ,Kg/s	Inlet (Avg). velocity (m/s)
(I)1-25	0.0900	3.47	17.54
(II)1-25	0.0900	3.51	18.23
(II)26-50	0.0968	4.47	18.30

6. RESULTS AND DISCUSSION

It is a well established fact, that in pneumatic conveying system, silica sand can only be conveyed in dilute phase suspension flow[22]. Various researches have also shown that a minimum pick up velocity of order 13 m/s is required for conveying silica sand. In phase 1 of the experimental test programme with 51 mm bore bends yielded an average air inlet and exit velocities of 17.54 m/s and 36.22m/s,respectively with bend impact velocities increasing althroughout the test loop.Experiments with modified test pipeline loop yielded an average air inlet velocity of 18.23 m/s ,average impact velocities of 8m/s and average exit velocity of 34.95m/s.Dilute phase suspension flow has been maintained successfully during the tests.

6.1 Bend Erosion In each test programme, at four locations bend erosion has been monitored. For this purpose weight loss of the bends are measured at regular intervals. Both test programmes have been carried out in similar conveying conditions. Weight loss details of 51 mm bore bends at all four locations in a single bore pipeline is shown in **table 2.**

Runs	Bend1	Bend2	Bend3	Bend4
2	12.1	14.1	16.1	17.8
7	29.6	32.1	36.7	45.8
8	34.3	35.7	38.8 **Failed**	49.3 **Failed**
10	38.9	39.9 **Failed**	48.0	60.1
13	42.6 **Failed**	50.0	55.8	74.4
15	48.9	53.3	60.5	79.5 **Failed**
19	53.3	55.9	63.7	89.6
25	60.3	60.8	71.3 **Failed**	99.6
Total	**60.3**	**60.8**	**71.3**	**99.6**

Table.2. Cumulative Weight Loss in Grams for 51 mm Bore Bends

It shows that bend number 3 and 4 have failed only after 8 runs of conveying silica sand. The cumulative weight loss for the fourth bend is highest (99.6gms). This seems to be due to the fact that at the bend number 4, the conveying gas velocity is of order 30 m/s, highest among all the other bends. This is due to the air expansion effect. The weight losses for the other three bends located at position 1 to 3 are found to be in increasing order. This is expected since the velocity of conveying and the velocity at which the particles impact on the bend is increasing from bend 1 to bend 3. Weight loss details of 102 mm bore bends at all four locations in modified test pipeline is shown in **table 3 .** Erosion rate for 102 mm bore bends in the modified test loop has been found to be much less compared to the bends of constant bore pipeline. Referring again to the bend number 4 of the modified loop, which is at the highest velocity amongst the four test bends, the cumulative weight loss is found to be 81.3 gms after 25 runs compared to 99.6 gms of 51mm bore bends at the same position. It is expected, as there is reduction in impact velocities at the bend by the virtue of tapered sections ie. improved bend geometry thus safer impingement angles. The impact velocities calculated at the bend are of order 8 m/s. In this case also the weight losses for the other three bends located at position 1 to 3 are found to be in increasing order.

Table.3. Cumulative Weight Loss in Grams for 102mm Bore Bends

Runs	Bend1	Bend2	Bend3	Bend4
2	9.8	10.1	14.9	15.2
7	15.6	19.5	29.1	34.7
13	21.4	28.0	45.5	51.4
19	24.3	38.5	52.2	67.0
25	28.4	47.5	57.7	81.3 **Failed**
30	31.3	48.9	62.3	91.0
35	33.9	53.6	66.8	100.4
40	36.7	59.2	67.9	109.3
45	40.7	62.4	69.0	114.3
50	44.7	67.9	70.0	119.3
Total	**44.7**	**67.9**	**70.0**	**119.3**

6.2 Modified Bend Geometry Experiments have shown that the conveyed particles made impact at an angle of 24^0 in 51 mm bore bends. Whereas; by virtue of bends with tapered sections the same particles made impact on the bend at an angle of 32^o shown in **fig. 4 & fig.5.**It is felt that the increase in the impact angle reduced the erosion rate of bends. Same facts have been also shown by various researchers that the ductile material offer good resistance above 20^o and the erosion resistance of the ductile material increase with the increase in the impact angle.

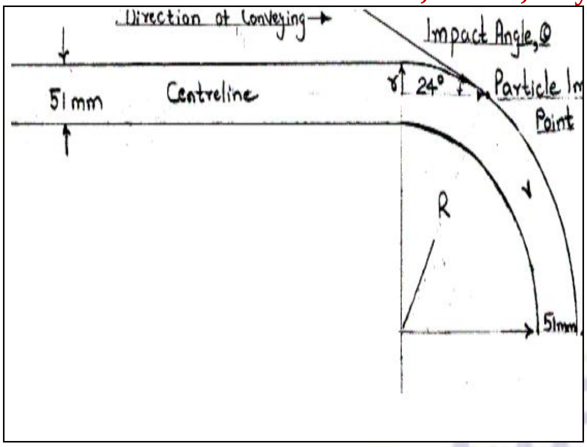

Fig.4. Dimensional Sketch of 51 mm Bore Bend

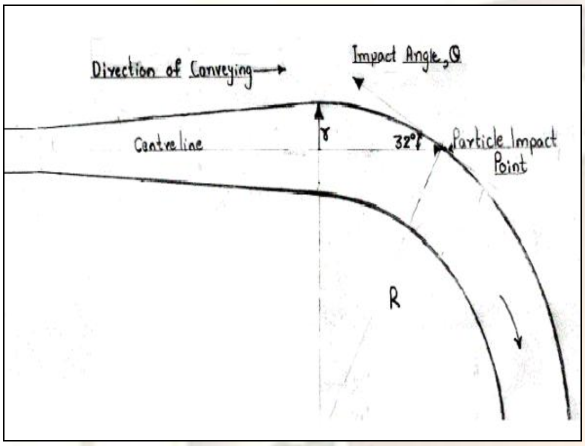

Fig.5. Dimensional Sketch of 102 mm Bore Bend

6.3 Product Degradation In pneumatic conveying situations, the size, the shape and the relative hardness of the particle dictates the erosion and the conveying performance of the system[23,24]. The mean particle size of fresh sand was found to be 212.5 µm by sieve analysis**.** The sieve analysis performed on sieve analyzer shows that the product degradation in 102 mm bore bends is much lower to 51 mm bore bends. The mean particle size of silica sand for phase-1 of the tests came out to be 106 µm after 25 runs that is much lower to the mean particle size of sand (135 µm) for phase- 2 of the tests after same number of runs, **table.4.**

S.No.	**Test Phase**	**Runs**	**Mean Particle Size µm**
1	I	25	106
2	II	25	135
3	II	50	125

Table.4. Mean Particle size of silica sand at different phases of tests

It is felt that the particles would spread out due to the divergent section of the pipeline immediately before the bend in modified loop and many particles would be swept with the flow of the gas without impacting at the bend, thus reducing the chances of product degradation.

6.4 Wear Profile The bends used in the experimentation process for both the phases is shown in **photo.1**. At the end of conveying tests, three bends shown in **photo.2** have been cut in to two halves along the centerline to examine the wear profile of the bend surfaces. Two failed bends of 51 mm bore showed very deep ripple formation with material removal mainly concentrated with in a narrow zone. Ripples have been also observed in the larger bore (102 mm) bends too; but it is not pronounced like in case of the smaller bore (51mm) bends.The material removal from 102 mm bore bend is spread over a larger area of cross section. It is felt that due to the gradual increasing area of cross section of pipeline before the entry to bend, the conveying air velocity have significantly reduced in case of tapered sections. As a result, wear in 102 mm bore bend is spread over much larger surface area. 51 mm bore bends showed no provision to reduce impact velocity, thus resulting in weight loss from a narrow concentrated zone.

Photo.1. Bends of 51mm and 102 mm bore used in the experimentation process

Photo.2. Wear Profile of 51 mm and 102 mm(centre) Bore Bends

7. CONCLUSIONS

The concluding facts of the comprehensive test programme carried out to study the effect of bend geometry on bend erosion and product degradation are summarized as follows:

- The bend erosion results have clearly indicated that using the bends of a larger bore in a small bore pipeline loop has a clear advantage in terms of the erosion rate of the bends.
- The material removal phenomenon in smaller (51 mm) bore bend is confined within a concentrated narrow zone with deep ripple formation. Wear in larger (102 mm) bore bend is spread over larger surface area with less ripples.
- The product degradation results show that velocity of impact is an influencing variable that causes damage to the product. So it is needed to be controlled precisely. The impact velocities obtained in case of the modified test loop are lower than the constant bore loop.
- Bends with modified geometry have shown their significance by showing improvements in the particle impact angle .This shows that favourable operating conditions like conveying air velocitiy and particle impact angle can be utilised to solve the potential problem of erosion and product degradation.

It is evident from the experimental tests concluded, that the solution proposed by way of modified pipeline loop has shown great potential in reducing the severity of bend erosion and this could prolong the bend life. The proposed solution could be safely recommended where product degradation during conveying is a matter of concern.

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